Assessment of the Accuracy of Interproximal Tooth Reduction using Three-Dimensional Digital Models

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Declaration

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Declaration of Ethics

The research presented and reported in this thesis was conducted within the guidelines for research ethics outlined in the National Statement on Ethics Conduct in Research Involving Human (1999) the Joint NHMRC/AVCC Statement and Guidelines on Research Practice (1997), the James Cook University Policy on Experimentation Ethics. Standard Practices and Guidelines (2001) and the James Cook University Statement and Guidelines on Research Practice (2001).

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Mark Blandy Date

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Nature of Assistance	**Contribution**	**Name, Title and Affiliations of Co-Contributors**
Intellectual Support	Proposal Writing	Prof. Andrew Sandham, Prof. Qingsong Ye; co-supervisors.
	Data Analysis	Prof. Qingsong Ye; supervisor.
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List of Acronyms

ARS: Air Rotor Stripping

DMFT: Decayed, missing, filled teeth

DMFS: Decayed, missing, filled surfaces

IPR: Interproximal Reduction

PDL: Periodontal Ligament

CBCT: Cone Beam Computerised Tomography

PAR: Peer Assessment Ratio

STL: Stereolithography

Abstract

Background: Interproximal reduction (IPR) demonstrates an alternative treatment option for orthodontic space gain in borderline extraction cases. Accurate IPR is essential to achieve proposed treatment objectives and becomes more frequently desired with the increasing popularity of digitally determined treatment plans. However there is currently limited evidence to support that it is an accurate technique to use. Limitations exist in extrapolating *in vitro* data to a real life clinically setting. For this reason studies are needed to evaluate the accuracy of IPR by means of quantification in an *in vivo* setting. The use of the Invisalign® system and 3-D digital models may aid the collection of data and the interpretation of the level of accuracy of IPR in a real patient setting.

Aim: To assess the accuracy of IPR as a method of orthodontic space gain using 3-dimensional digital study models. The null hypothesis for this study states that there is no statistically significant difference when comparing proposed and actual amounts of IPR completed (accuracy); the accuracy of IPR within and between upper and lower dental arches; the accuracy of IPR within and between posterior and anterior arch segments.

Materials and Method: Using 3-dimensional models gained via Invisalign's® ClinCheck, pre and post IPR data are available from actual patient cases. Recording of the width of the teeth before and after IPR at case refinement demonstrates how much IPR was actually completed. The proposed total amount of IPR is pre-determined and compared to the actual amount and the difference recorded as a measure of accuracy. A level of clinical significance will also be determined. All measurements are completed using Geomagic Control 2014 (Rock Hill, USA) digital design software.

Results: The results indicate that IPR was not completed with a high degree of accuracy and that the amount of reduction was generally much smaller than what has been determined. Overall IPR was under-achieved by 55.9% per tooth surface in the sample assessed. On average 0.188 mm of IPR was aimed to be completed per tooth surface however only 0.083 mm was actually achieved, showing a significant discrepancy of 0.105 mm per tooth surface. No significant difference was found in IPR accuracy between the upper arch (an average 60.5% under-achievement per tooth surface) and lower arch (an average 49.4% under-achievement per tooth surface) ($p=0.062$). Also, no significant difference was found in IPR accuracy between the anterior segment (an average 58.6% under-achievement per tooth surface) and posterior segment (an average 42.3% under-achievement per tooth surface) (p=0.352).

Conclusion: IPR might not be completed with a high degree of accuracy and it is generally much smaller than what is trying to be achieved. Clinicians should acknowledge these findings and critique their own technique of IPR accordingly to ensure the highest standard of treatment outcomes.

CHAPTER 1: INTRODUCTION AND AIM

1.1 Introduction

Interproximal reduction (IPR), also known as enamel stripping, reproximation, or slenderisation, involves removal of enamel from the mesial and/or distal contact area. It can be done on anterior or posterior teeth, during or after orthodontic treatment with fixed or removable appliances. The main indication is to gain space to align teeth, but it may also aid in correcting tooth size discrepancies, improving stability, and for aesthetic considerations.

IPR is not a new concept and was introduced by Ballard[1] in 1944, who suggested it's used mainly for the anterior segment when a lack of balance presents. In 1953, Begg[2] published his study of Stone Age man's dentition, which referred to the shortening of the dental arch and contributed to the development of the technique for IPR. The use of medium and fine metallic strips for mesiodistal reduction followed by final polishing and topical fluoride application was introduced by Hudson[3] in 1956 in the first clinical sequence as IPR. The use of fluoride post-IPR has had continued support by other authors[4,5].

The dimensions of the dental arch in terms of arch length, depth, and inter-canine width are continually decreasing over time not only in the normal untreated individual but also in people who have previously undergone orthodontic treatment[6,7]. The resultant shortage of space is shown as tooth displacement or crowding. Sheridan proposed that IPR with an air-rotor technique is similar to the natural processes of interproximal wear over time[8].

Methods by which space can be gained in a dental arch include dentoalveolar expansion, proclination of anterior teeth, distalisation of molars, extraction, and IPR. For every 10 degrees of proclination of anterior teeth, 4 mm in arch perimeter is gained[9]. Extraction of teeth and expansion of dental arches are typical ways of gaining space in an orthodontic patient. To resolve crowding in non-extraction treatment however the arch length is often increased which has been associated with instability and future relapse. IPR has become an alternative to extraction of permanent teeth or arch expansion in cases of moderate (4-8 mm) crowding, which makes it an appealing choice in the treatment of adults especially.

Short and long term follow up studies have shown that after extensive grinding of enamel towards the dentin, no harmful side effects are observed as long as adequate cooling is used during the procedure and the tooth surface is left smooth and self-cleansing[10]. With adequate polishing after the reduction process, enamel has the potential to be left smoother than untreated enamel[11-15], eliminating the risk of plaque accumulation and subsequent dental caries[10,16-19].

The process of IPR demands precise clinical skills to achieve the desired reduction potentially down to 0.1 mm. If over reduced, residual space may appear which rarely closes spontaneously. If under reduced, the appropriate amount of space desired for tooth movement won't be available and alignment will not be achieved. The accuracy of the procedure has only limited data available, all of which is based on *in vitro* based studies[11,20]. No study has investigated the accuracy of IPR in an *in vivo* setting as a means for orthodontic space gain. The scanning of silicone impressions or plaster models to create three dimensional digital models is a popular and cost effective means for construction of study models. The use of these three dimensional digital models for linear measurements has been determined accurate in comparison to the use of traditional study models[21-27]. Further information needs to be gained in a clinical setting as to the accuracy of IPR to prevent excess space, malaligned teeth, or inter-arch discrepancies persisting. This study will investigate the accuracy of IPR in an *in vivo* setting using 3 dimensional digital models.

1.2 Aim

The objective of this study is:

- To assess the accuracy of IPR as a method of orthodontic space gain using 3-dimensional digital study models of *in vivo* data.

  - Any outcome will help orthodontic clinicians in treatment planning and assist in the clinical judgement of completing interproximal tooth reduction on patients.
  - The study will provide some base line *in vivo* data as to the accuracy of IPR to which future studies of larger sample sizes can use for comparison and further statistical analysis.

CHAPTER 2: LITERATURE REVIEW

Peck and Peck[28] introduced IPR with an evaluation of terminology relating to the process. "*This procedure is called 'stripping'. Although part of the orthodontic vernacular, 'stripping' is a somewhat distasteful term. Articles and texts frequently resort to euphemisms, such as 'proximal reduction'.....In place of 'stripping' we propose 'reproximation', a word whose derivation implies 'the act of redoing the approximal surfaces. Tooth reproximation is a clinical procedure involving the reduction, anatomic recontouring, and protection (via acidulated phosphate-fluoride) of the mesial and/or distal enamel surfaces of a permanent tooth".* Despite their appraisal the term interproximal reduction (IPR) is felt to be the most applicable term as it describes the actual removal/reduction of tooth structure of one or both interproximal surfaces of a contact point and will be used throughout this text.

2.1 History of Interproximal Wear

The intentional removal of interproximal tooth structure accomplished with IPR has developed from natural processes found in human dentitions. Interproximal attrition or wear as a means to naturally gain space in dental arches to align teeth more favourably is more prevalent in underdeveloped non-industrialised populations who eat rough harsher foods compared to industrialised populations who consume processed foods. It has been proposed that the process of interproximal wear is an adaptive change which decreases dental arch length to allow space for emerging third molars, as demonstrated in studies of Australian Aboriginals[2]. Little to no crowding has been found by anthropologists in the remains of primitive dental arches. This theory of 'attritional occlusion'[2] that was based on arch length reduction due to mesial tooth migration during interproximal wear, was responsible for Begg's orthodontic principles.

"It is a prerequisite that the inherited sizes of all of deciduous and permanent teeth, before they become worn, be greater than can be held by the tooth bearing parts of the jaws…Unless there were excess of tooth substance relative to jaw size, Stone Age man would, early in life, have insufficient tooth substance to occupy fully the tooth-bearing parts of his jaws because tooth attrition is so extensive."[2] Begg also believed that due to the developmental advancements in modern society and production

and consumption of softer and more refined foods, people of today have more crowding due to a lack of natural interproximal wear.

It has been explained that interproximal wear is related to a mesial force that tends to maintain the teeth in proximal contact, and a bucco-lingual force arising from lateral masticatory movements[29]. The result is a contact 'area' rather than a contact 'point' seen as a concave area on the mesial surfaces of teeth with the distal surface of the adjacent tooth retaining its normal convex outline (Figure 1). According to Kaidonis[30] there is a direct relationship between occlusal load and interproximal wear and the mesial migration of teeth. This heavy occlusal load develops from eating fibrous and hard foods, often including bones, and is responsible for a relative movement of adjacent teeth with resultant interproximal wear. Interproximal grooving has been analysed by Brown and Molnar[31] in Australian Aboriginals but the cause has been related to the use of teeth as accessory implements for making tools and stripping of fibrous material between the teeth. Sarig et al[32] conclude that the interproximal arrangement of the permanent dentition is most likely a result of physiological attrition dictated by masticatory forces. They suggest that knowledge of this interproximal interface should influence characteristics of crown and filling designs, and influence tooth alignment with the aid of IPR.

Begg's theory of attritional occlusion has since been challenged[33] but the idea of interproximal tooth wear has had an influence on modern principles to eliminate crowding such as interproximal tooth reduction.

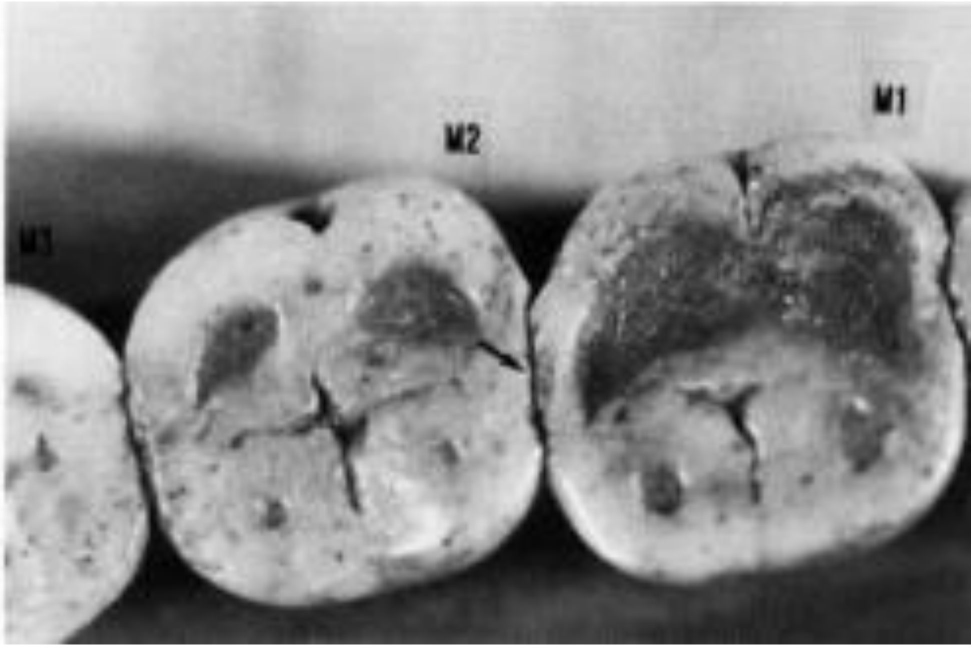

Figure 1: Image showing interproximal tooth wear.

Adapted from *Kaidonis 1992.*

2.2 Indications for Interproximal Reduction

IPR is usually indicated when there is inadequate arch length to accommodate all the teeth and extraction would result in an excessive amount of space available. It is also indicated when individual tooth sizes prevent a Class I molar and canine relationship from being established. A Class I canine relationship is desired as it will create enough space mesial to the canines to accommodate the lateral and central incisors. Similarly, a Class I molar relationship will create enough space to accommodate the first and second premolars, and the canine and incisor teeth further forwards in the arch.

In borderline extraction cases there are benefits not to extract and manage the case instead with IPR. Benefits include the avoidance of unfavourable profile changes from retroclining incisors, an increased probability of a stable result, a reduction in treatment time compared to extraction treatment, and a reduced risk of orthodontically induced root resorption[34].

IPR is also useful in reshaping teeth to avoid unsightly black interproximal spaces developing.

2.2.1 Discrepancies in Tooth Size and Inter-Arch Size

An interarch tooth size discrepancy is seen when there is a disproportion in the mesiodistal widths of teeth in opposing arches. In the absence of a proportional match in size of upper and lower teeth, a normal occlusion is impossible[35]. Clinical findings commonly associated with a discrepancy between the upper and lower arch include crowding or spacing of incisors, excessive or deficient overjet, excessive or deficient overbite, canines not in Class I when a Class I skeletal pattern exists, wear and compensatory eruption of anterior teeth, and abnormal angulation and inclination of incisors and canines[36]. Measurement of the mesio-distal widths of teeth is usually conducted on study models but can be completed intra-orally. When measuring tooth width to determine tooth size discrepancies, a Boley gauge provides consistently more accurate measurements than a needle-pointed divider[37].

Ballard[1] studied asymmetry in tooth size and found that 90% of his sample had right/left discrepancies in tooth width. If tooth size discrepancies are left unattended, final stability cannot be achieved and will result in rotations and slipped contacts. He identified and recommended the need for IPR when a lack of balance existed particularly in the anterior segments. An arch length discrepancy could be the result of excessively large lower anterior teeth, but is more commonly due to smaller upper anterior teeth, particularly the lateral incisors.

Clinical management of a tooth size discrepancy between the upper and lower arches is recommended when the required tooth size correction is greater than 2 mm[38]. This will require either the addition of tooth width via a restorative means, or removal of tooth width via IPR. The decision needs to be made as to whether restorative widening of one dental arch, mesiodistal reduction of the opposing dental arch, or both, are to be completed to resolve the interarch space discrepancy.

The Bolton analysis[39] was developed to estimate the likelihood of the maxillary dental arch occluding with the mandibular dental arch in a Class I molar relationship. The analysis looks at the ratio of the summated mesiodistal widths of the mandibular to maxillary teeth compared with standardised values in order to quantify a discrepancy. This is from either first molar to first molar, or canine to canine in the upper and lower arches. Comparison of tooth sizes in the upper arch to tooth sizes in the lower arch by means of ratios helps to decide whether there is an excess, ideal, or deficient relationship i.e. Are the maxillary teeth too narrow/wide; are the mandibular teeth too narrow/wide? The relation determined by the Bolton analysis between the upper and lower first molar to first molar tooth size is 91.3 +/- 1.91. The canine to canine relationship is 77.2 +/- 1.65. A figure falling within one standard deviation of these ratios will assist the development of a Class I relationship. The measured percentage can be compared with the normal percentage to determine if the tooth disharmony is a maxillary or mandibular tooth problem. Despite the Bolton's values, it has been found that using the standard deviation of the variance is not an accurate guide for a clinically significant tooth-size discrepancy[40].

2.2.2 Elimination of 'Black Triangles'

Aesthetic needs not only focus on alignment of the teeth but also include aspects of the smile such as the gingival tissues. One factor that is often seen as unsightly by patients is an open gingival embrasure or black gingival triangle. 'Black triangles' are seen mainly in patients post-treatment if the interdental contact points are located too far incisally, or when there may be loss of periodontal support from plaque associated lesions. Crowns may also be triangular shaped, or there may be improper root angulation as contributing factors. The prevalence of these black triangles has been shown to be present in 41.9% of adolescent patients treated for crowding of the upper central incisors[41].

In the absence of interdental papillae, black gingival triangles or papillary recession may be visible. As the distance of the interproximal contact point to the upper border of the bone crest increases, it is less likely that the interdental papilla will be adequate to fill the space created and a black triangle may persist (Figure 2). For this reason it has been advised that this distance does not exceed 4.5-5 mm. This was demonstrated by Tarnow et al[42] who measured the presence or absence of the interproximal papilla relative to the distance between the base of the contact point to the crest of bone. If a space is visible apical to the contact point, the papilla is regarded as missing, vice versa. The authors showed that if the distance from the contact point to the end of the interdental bone crest is 5 mm or less, the papilla is present in almost 100% of cases. If the distance increases to 6 mm, the papilla is found in 56% of cases, and if it is increased further to 7 mm or more, the papilla is only present in 27% or less of cases.

Triangular shaped teeth are more likely to show a ‘black triangle’ and therefore should be strongly considered for IPR and reshaping to develop a lower contact point and better gingival harmony. According to Kokich et al[43], orthodontists are more perceptive than general dentists and lay persons in detecting dental aesthetics. Orthodontists found a 2 mm open space between the upper central incisors unattractive, while general dentists and lay people were only able to detect an open gingival embrasure 3 mm or more. Such small spaces therefore may not be enough to commence orthodontic treatment in the average patient. These gingival deficiencies may also lead to chronic food impaction and increased dental disease.

In a text by Bennett and McLaughlin[44] it is suggested that black triangles are not always the result of an increased distance between the contact point and the bone crest. Such triangles can occur with poor bracket position with respect to the inclination of a given tooth. In such a case IPR is not indicated but rather bracket repositioning is required.

Figure 2: Image of papilla recession/black gingival triangle.

Measured by the distance between the papilla tip (PT) and the contact point (CP).

Adapted from *Tarnow 1992.*

2.2.3 Increased Post-Orthodontic Stability

One goal of orthodontic treatment is to achieve long-term stability of the occlusion and maintain the treatment result. In a comparison of mechanical arches to dental arches, Lasher[45] concluded that engineers that work with broad flat blocks have an advantage of less mechanical slippage compared to the dental arch and teeth which are rounded and fit at a small contact point. This analogy was used to look at relapse of lower anterior crowding ultimately due to the shape of the teeth. Some authors believe that IPR will increase the stability of orthodontically aligned teeth[46-49]. It has been proposed that flattening of the contact points in the lower anterior region will help in reducing or preventing relapse due to the proximation of the flat contact. A broad contact area rather than a contact point is developed. Paskow[50] has suggested that given the right case selection, IPR could be done without the need for fixed or removable appliances to align teeth. Aasen and Espeland[51] used IPR as part of their overall approach to maintain orthodontic alignment of lower incisors without the use of retainers and suggested that it is a realistic option for patients in the long term. However such stability related to IPR is yet to be confirmed with any statistical significance.

2.2.4 Creating Space for Better Alignment

Many orthodontists believe that the alignment of the mandibular arch serves as a template around which the upper arch develops and functions. Proper positioning of the mandibular incisors is considered by Little[52] to be the most important goal in achieving good results. IPR is a useful way of creating space in non-extraction cases. If, for example, 14 teeth were present in an arch and 0.6 mm of contact point reduction was completed from the mesial surface of the most posterior tooth on the right to the mesial surface of the posterior tooth on the left, a total of 7.8 mm of space can be created. Some authors advocate that it is safe to remove even greater amounts of enamel, further increasing the possible amount of space to be created (see 'How much enamel is safe to remove'). If even more space is required, other orthodontic techniques such as proclination of incisors, arch expansion, de-rotation of teeth, molar distalisation, and arch form development can be used either with or without minimal amounts of IPR rather than excessively reducing multiple teeth. According to Kirschen et al[53,54], tooth reduction may be used to reshape an individual tooth or to relieve small amounts of crowding. Also space is gained from reducing the mesiodistal width of an unusually broad tooth.

Orthodontists would not normally measure buccolingual diameters of teeth as they are more concerned with the mesiodistal widths of teeth in relation to the available space of the jaws. The index for assessing tooth shape deviations as applied to the mandibular incisors developed by Peck and Peck[28] uses the mesio-distal to facio-lingual (MD/FL) ratio to determine whether a lower incisor is favourably or unfavourably shaped to achieve good anterior alignment. The clinical guidelines follow a maximum desirable MD/FL index value of 88%-92% for the mandibular central incisors, and 90%-95% for the mandibular lateral incisors. Patients whose mandibular incisors have MD/FL indices above the desired ranges are considered candidates for the removal of mesial and/or distal tooth structure as part of their orthodontic treatment. Sarig et al[32] have suggested that IPR should mainly be performed in the occlusal half of mandibular incisors, and the gingival half of canine teeth to ensure correct alignment of teeth post-reduction.

2.3 Contraindications for Interproximal Reduction

2.3.1 Poor Oral Hygiene

IPR must be avoided in patients with poor oral hygiene or a high caries risk. The removal of enamel structure makes the vulnerable dentine and pulp tissue more easily accessible by micro-organisms in cariogenic biofilms. However the validity of any orthodontic treatment in patients with poor oral hygiene in the first place should be seriously considered. Radlanski et al suggest the process of IPR itself roughens the remaining enamel surface potentially allowing biofilms to accumulate more readily[55]. However modern techniques have shown that IPR completed with adequate polishing can leave enamel smoother than untreated enamel[13,15].

2.3.2 Dental Factors

IPR is an irreversible procedure and there is a risk of over-reduction of enamel from aggressive technique or poor pre-operative assessment with loss of tooth contours and the possible need for restorative resurrection. Teeth that are severely rotated should not undergo IPR as the proper contact area is not accessible and enamel would be removed from the incorrect location. In these cases crowding should be relieved or interproximal separators should be placed to create space between adjacent teeth prior to the procedure. Teeth that are hypersensitive to cold should be avoided for the risk of exacerbating the sensitivity and contributing to pulpitis.

Poor control of instruments may result in soft tissue damage e.g. gingival tissue and buccal mucosa. High speed spinning instruments can easily make their own path of reduction and slice teeth.

2.4 Consideration of Enamel

2.4.1 Enamel Thickness

It is extremely important to know the thickness of enamel on different teeth before undertaking IPR. Variations exist between anterior and posterior teeth, mesial and distal surfaces of the same tooth, as well as between the incisal/occlusal surface and the cemento-enamel junction. Mesial and distal dimensions are the most important when considering IPR.

Dentists' perception of enamel thickness of posterior teeth from radiographs assessed by Grine et al[56] found a general overestimation of measurements made from radiographs and a large variability of error. This stresses the importance of having an appreciation of a numeric average value of enamel thickness prior to undertaking IPR.

Enamel is a non-vital tissue that is unable to regenerate. With age the pores decrease in number as more ions accumulate between the crystals[57]. Thus it becomes less permeable whereas young enamel allows the passage of water and substances of small molecular size between its crystals. It may be concluded that young enamel is equally permeable from the inner dentinal surface, while old enamel is no longer permeable from the outer surface. A variation in permeability could exist at different levels from the outer surface towards the dentinal surface and this could also vary at different age levels of enamel post-eruption. This is an important point to consider as IPR on an immature enamel surface may predispose that tooth to increased post-operative sensitivity and potentially at an increased risk of dental caries. In a study by Kotsanos et al[58] a decrease in susceptibility to caries with increasing age was observed. It was proposed that a process of maturation occurred post-eruption that contributed to a reduction in permeability of enamel that would continue to occur with age.

Results released by Shillingburg and Grace[59] on the thickness of enamel and dentine served as the scientific basis for the amounts of IPR that could be undertaken in a safe manner. Hall et al[60] reported thickness variations of enamel between mandibular lateral and central incisors as observed in Table 1. Measurements were made off periapical radiographs at the maximum crown width. It was found that enamel thickness on the distal surface was significantly thicker than that on the mesial surface for both central and lateral incisors, and the enamel thickness on the mesial and distal surface of the lateral incisor was thicker than that of the central incisor. The difference between the mesial and distal surfaces of the lateral incisor is large enough to influence the quantity of planned enamel reduction. The author also suggested that if planning to undertake IPR on a patient the thickness of enamel should be estimated from radiographs that have been calibrated to the width of the tooth measured from study models or intra-oral measurement to avoid magnification error.

A study by Harris and Hicks[61] looked at enamel thickness in maxillary incisors. Measurements were made at the maximum crown width assessed perpendicular to the tooth's long axis on periapical radiographs. Enamel thickness was significantly thicker on the distal than the mesial of both lateral and central incisors. The measurements in Table 1 are given for upper right central and lateral incisors.

A study completed by Stroud et al[62] looked at enamel thickness of the mandibular posterior teeth. Bitewing radiographs were digitised and enamel thickness measured at the maximum mesio-distal thickness of the tooth. Molar enamel was significantly thicker than premolar enamel. Significantly greater thickness of distal enamel compared to mesial enamel was recorded in all posterior teeth except the second premolar, but the distal surface was still thicker than the mesial. The following thicknesses are observed in Table 1.

All the figures listed suggest that the distal surface always has a thicker proportion of enamel compared to the mesial. It must be kept in mind that the average enamel thickness of a tooth is the entire enamel thickness, and not the amount of enamel available to be removed. Not every tooth abides to the average thickness of enamel and so to prevent iatrogenic damage to the tooth the minimum amount of enamel should be aimed for removal.

MAXILLARY	Mesial	Distal	Total
Central Incisor	0.90±0.12	1.05 ± 0.15	1.95 ± 0.14
Lateral Incisor	0.91 ± 0.12	1.01 ± 0.12	1.92 ± 0.12
MANDIBULAR			
Central Incisor	0.72 ± 0.10	0.77 ± 0.11	1.49 ± 0.11
Lateral Incisor	0.80 ± 0.11	0.96 ± 0.14	1.76 ± 0.13
First Premolar	0.99 ± 0.21	1.07 ± 0.23	2.06 ± 0.22
Second Premolar	1.19 ± 0.21	1.22 ± 0.22	2.41 ± 0.22
First Molar	1.28 ± 0.23	1.40 ± 0.25	2.68 ± 0.24
Second Molar	1.29 ± 0.20	1.48 ± 0.26	2.77 ± 0.23

Table 1: Average mesial and distal enamel thicknesses measured at the maximum crown width (mean ± sd mm).

Adapted from *Hall et al 2007, Harris and Hicks 1998 and Stroud et al 1998.*

2.4.2 How Much Enamel is Safe to Remove?

It has been estimated that up to one half of the enamel thickness could be removed with minimal or no negative effect on the tooth[3,46]. Hudson[3] suggested 0.20 mm can be reduced from lower central incisors, 0.25 mm for lower lateral incisors, and 0.30 mm for lower canines. This gives a total of 3mm of potential space to be gained for the lower anterior segment. In comparison, Tuverson[47] suggested that 0.3 mm per proximal surface of lower incisors and 0.4 mm per canine, giving a total of 4 mm of potential space to be gained in the lower anterior segment. Sheridan[63] instructed up to 0.8 mm of reduction for each surface per posterior tooth and 0.25 mm in the anterior teeth to give a total of 11 mm of available enamel to be reduced from first molar to first molar. Other authors generalise the specifications of maximum reduction. Alexander[64] advises only 0.25 mm of reduction for any tooth, either anterior or posterior to give a total of 5.5 mm of available space from the mesial of a first molar to the mesial of a first molar.

A table published by FIllion[65] gives the upper limits of enamel substance that can be removed. According to this table, "*Orthodontists should assign priority in stripping to the posterior teeth, because any malfunction in stripping of the incisors might disfigure them*." Using Table 2 as a guide

10.2 mm in the maxilla and 8.4 mm in the mandible can be gained by undertaking IPR from the mesial of one first molar to the mesial of the other first molar.

Although it is good to have numerical values to assist in determining the amount of enamel that can be removed during an IPR procedure, it must only be used as a guide and individuality must be taken into account. Asymmetries should be compensated for by removing more or less enamel in the opposite quadrant and the midlines must be centred. In the posterior segments the cusps should remain intercuspated. Also, the point of the interdental papilla should line up with the contact point as not to give the impression of incorrectly inclined teeth. Whenever undertaking IPR it should be done in stages reducing the minimal amount each time as to prevent over reducing the tooth. Accurate reference data should be used to help estimate the actual amount of tooth structure that can be removed.

No relationship has been identified between tooth shape and enamel thickness, therefore the amount of IPR cannot be varied for a given crown shape and enamel thickness should still be used as a guide. Yet dental shape is still of great importance. Common crown shapes include rectangular, triangular, and barrel-shaped teeth. Rectangular shaped teeth have a broad contact point with no visible spaces. Triangular shaped teeth on the other hand have a reduced occlusal or incisal contact point predisposing individuals to 'black gingival triangles'. Barrel-shaped teeth tend to have contact points in the middle showing separation towards the incisal edge. In general it would be advised to undertake IPR on larger teeth rather than smaller microdont teeth even though tooth shape has no influence on enamel thickness. If restorations and crowns are over-dimensionalised to close spaces, they should be reduced for adequate interdigitation post-orthodontics.

Pre-treatment gingival and incisal spaces from either triangular or barrel shaped teeth may not be visible due to crowding. As the teeth are unravelled and aligned the spaces may become more evident, in which case the majority of patients will not accept this as a result. IPR is indicated in both situations to give a more aesthetically pleasing final result. Also, it is important to remember that contact points of posterior teeth are more apical than contact points on anterior teeth. The contact point shows the greatest thickness of enamel where thickness decreases towards the cemento-enamel junction.

Baysal et al[66] looked at the temperature rise in the pulp chamber during different IPR procedures as an increase in temperature can result in pulpal inflammation. IPR procedures done with a tungsten carbide bur showed a greater temperature rise compared to metal strips and perforated discs when used without coolant. This was significant when reducing mandibular incisors and may relate to its smaller enamel dimensions. When considering a coolant method to prevent heating the pulp, air is better than water spray to aid in greater visibility during the procedure.

	Central		Lateral		Canine		First Premolar		Second Premolar		First Molar	Total Per Arch
	M	D	M	D	M	D	M	D	M	D	M	
Upper Arch	0.3	0.3	0.3	0.3	0.3	0.6	0.6	0.6	0.6	0.6	0.6	10.2
Reduction per Contact Point	0.6	0.6		0.6		1.2		1.2		1.2		
Lower Arch	0.2	0.2	0.2	0.2	0.2	0.2	0.6	0.6	0.6	0.6	0.6	8.4
Reduction per Contact Point	0.4	0.4		0.4		0.8		1.2		1.2		

Table 2: Maximum amount of enamel to be removed (mm) with interproximal reduction.

Adapted from *Fillion 1993.*

2.4.3 Enamel Quality after Interproximal Reduction

Rough surfaces will promote biofilm formation and maturation therefore smooth enamel surfaces are indicated to reduce the occurrence of caries and periodontitis. Numerous *in vitro* studies have examined the surface quality of enamel via SEM after using different methods of IPR. Radlanski et al[55] conducted a study in 1988 with a combination *in vitro* and *in vivo* component. The *in vitro* part involved IPR on extracted teeth and surface characteristics were assessed under SEM. The *in vivo* part involved IPR on teeth planned for extraction but the teeth remained intra-orally for 12 weeks prior to extraction and SEM assessment. The patients were instructed to either use or not use dental floss daily. Different protocols of IPR were used but despite this it was found that it was not possible to leave the enamel completely free of furrows initially caused by a coarse stripping implement. The depth of these furrows were deep enough to accumulate significant levels of biofilm which could not be removed with dental floss. This study prompted further investigations into the long term health risks for dental enamel post-IPR and inspired others to identify a method of IPR that could give the most favourable surface characteristics for enamel.

Piacentini et al[13] found that when using an 8-straight blade tungsten carbide bur followed by Sof-Lex discs it is possible to obtain well-polished surfaces that may appear smoother than the intact or untreated enamel. This study also explored the concept of a combination mechanical and chemical means of IPR but proved it to be ineffective. Results shown by Zhong et al[15] also confirmed that with correct clinical application enamel can be left smoother than untreated enamel. This technique introduced the use of a perforated stripping disc on an oscillating handpiece followed by polishing with fine and extra-fine Sof-Lex discs. The results showed that more than 90% of the reduced enamel surfaces were smoother than untreated enamel. A potential flaw in the study design however was that the reduced and polished surfaces were replicated with impression material and cast in epoxy resin prior to SEM evaluation. Therefore the assessment was not of the original enamel surface and the replica may not be a true representation.

Danesh et al[11] showed the use of coarse strips or burs leave irregularities that cannot be smoothed effectively even with subsequent polishing. However the use of automatic oscillating systems can leave a significantly smooth enamel surface if followed by polishing. No acid etchant were introduced into the polishing protocol.

Joseph et al[12] also used SEM to look at surface roughness of enamel post IPR with different mechanical and chemical methods. In addition they assessed the effects of a synthetic calcifying solution on the etched enamel. The results showed that teeth stripped by routine mechanical abrasive methods exhibited deep furrows and roughness which are potential areas for biofilm accumulation. The teeth that received mechanical and chemical abrasive treatments showed a flattened, etched surface free of furrows. These etched surfaces showed marked crystal growth after remineralisation suggesting the possibility of repair of the chemically altered enamel surface. That is, the chemically stripped enamel invites the possibility of repair by remineralisation. Overall, chemical in combination with mechanical reproximation eliminates the disadvantages formed by mechanical stripping alone by creating a relative smooth surface that has the potential to heal itself by remineralisation. These finding are supported by Rossouw and Tortorella[14] who found that the use of acid stripping in conjunction with mechanical procedures produced especially smooth enamel surfaces. Both 35% phosphoric and 10% maleic acid were used in the study and recommended for daily clinical practice as an adjunct to the polishing procedure. If an acid etchant is used as part of the polishing process in an attempt to maximise smoothness, fluoride should be considered to enhance the remineralisation potential of the enamel surface. Despite findings that chemical etchants can be incorporated for final polishing of stripped enamel surfaces some studies have suggested otherwise, stating that polishing combinations with the use of acid etchant in fact leave enamel rougher than other techniques[13,67,68]. The various methods mentioned show that there is evidence for and against the use of chemicals to be incorporated into routine IPR methods of polishing. No study has assessed the outcome of using acid etchant in the polishing process after reduction with an oscillating handpiece.

IPR should be undertaken only in patients with adequate oral hygiene practices and a low caries risk to avoid increased caries susceptibility. The furrows caused by mechanical reduction may increase the predisposition for biofilm retention[69,70]. It has been found that the use of dental floss cannot prevent biofilm accumulation at the bottom of the furrows formed in enamel after reduction[55]. Artificially roughened enamel is less resistant to penetration of a lactate buffer and it advised that fluoride treatment be applied for a lengthy period after IPR[5]. An *in vitro* study by Twesme et al[71] looked at the effects of air-rotor stripping on the susceptibility of human enamel to demineralization. 0.5 mm of IPR by air-rotor stripping was completed on the crowns of 48 extracted premolar teeth on one proximal surface. Teeth were then placed in a demineralisation gel for various time intervals and the lesion depth on the reduced and untreated proximal surfaces were analysed. The results showed that air-rotor stripping significantly increases the susceptibility of proximal enamel surfaces to demineralisation.

Despite these findings extensive and credible *in vivo* data available is suggestive that IPR does not result in increased susceptibility to caries or periodontal disease. Zachrisson has looked at numerous cases of IPR in relation to the short and long term effects of the remaining tooth structure[10,18,19,48,72]. A study in 1975 by Zachrisson et al[48] evaluated the changes in dentin and pulp following different IPR procedures. Teeth planned for extraction for orthodontics reasons were stripped with diamond wheels and discs and subsequently polished. Teeth were then sectioned and examined under a light microscope for alterations in the predentin/odontoblast region and for vascular and cellular changes in the pulp tissue subadjacent to ground areas. The study found that most felt sensitivity to hot/cold for 1-3 days after reduction. Premolars extracted immediately after grinding showed no histologic changes in pulp and dentin, while the remaining extracted teeth showed only limited changes histologically. The study provided histologic and clinical evidence to indicate that even extensive re-contouring by grinding may not be harmful to the teeth. In 2007 Zachrisson et al[19] conducted a 10 year follow up on anterior teeth that received IPR by fine diamond discs with air cooling followed by polishing. The sample consisted of patients who had received mesio-distal enamel reduction of all 6 mandibular anterior teeth more than 10 years previously. The results found that IPR did not increase iatrogenic damage. Dental caries, gingival problems, or alveolar bone loss did not increase, and the distances between the roots of the teeth in the mandibular anterior region were not reduced. This was supported by a recent retrospective study[18] that found no increased risk of caries in posterior teeth after IPR. There was no evidence that proper mesio-distal enamel reduction within recognized limits and in appropriate situations will cause harm to the teeth and supporting structures.

Clinical findings by Zacchrison are supported by Jarjoura et al[16] who compared the susceptibility of air rotor stripping (ARS) treated enamel surfaces with intact surfaces in patients undergoing fixed orthodontic therapy. The retrospective study used decayed, missing, filled tooth (DMFT) and surface (DMFS) scores to evaluate the subjects' overall caries risk. The DMFT and DMFS scores increased significantly during the study period, indicating that these patients were clearly at risk of tooth decay. However, the number of interproximal lesions detected was found to be low with no statistically significant difference detected between the groups. The overall conclusion was that the risk of caries is not affected by ARS.

An assessment of enamel after IPR using a laser fluorescence method (DIAGNOdent pen) showed that with correct diagnosis, as well as selection of intact or even slightly demineralised enamel surfaces, successful implementation of enamel reduction contained to within the enamel surface is possible[17].

Finally, a recent systematic review by Korestsi et al[73] evaluated the degree of enamel roughness and incidence of dental caries after interproximal enamel reduction. Teeth that had previously undergone IPR had the same incidence of dental caries as intact enamel surfaces showing that there is no increased risk of developing dental caries after IPR has been completed.

2.4.4 Enamel Quantity after Interproximal Reduction

If an orthodontic treatment plan indicates IPR it is important to be able to complete the procedure by the exact amount required. The amount of IPR depends upon several factors including enamel hardness, pressure applied, hardness and particle size of the abrasives, and the time spent undertaking the procedure[74]. In addition polishing with finer abrasives is required to remove grooves caused by the coarse abrasives resulting in further enamel loss[13]. Many studies have considered the surface characteristics after IPR but limited studies have focused on the quantity of enamel and the accuracy of the IPR. Some attempts to quantify enamel reduction have focused on surface roughness tests using profilometry which quantifies the amount of roughness rather than the true amount of reduction[67,68]. Only two studies provide a quantitative analysis of enamel reduction[11,20].

Danesh et al[11] used digital subtraction radiography to assess the accuracy of five systems including Profin, New Metal Strips, O-Drive D30, Air Rotor reduction, and Ortho-Strips on extracted lower incisor teeth. The extracted teeth were embedded in a silicone base to imitate the physiologic mobility of natural teeth. The results found no difference between the amount of IPR completed and that what was aimed for except for the O-drive D30 system which removed significantly more enamel than desired. The amount of enamel removed when polishing with fine abrasives after bulk reduction was also examined and shown to be between 0 and 0.02 mm which can be regarded as clinically insignificant.

Only one other study by Johner et al[20] has examined the predictability of the expected amount of IPR. They analysed three different methods of IPR on extracted premolar teeth including hand strips, oscillating disks (O-drive D30), and motor driven abrasive strips (Orthofile). The extracted teeth were embedded in silicone following the technique described by Danesh et al[11]. Quantification was assessed with a 3-dimensional laser scanner and a method of digital superimposition. Large variations were seen between the intended and the actual amounts of reduced enamel and between reduction systems. In most cases the actual amount of reduced enamel was less than the intended amount of enamel reduction. The actual technique used for IPR was determined an insignificant predictor for the actual amount of enamel removed.

The two papers that provide a true quantitative analysis of enamel reduction present varying results despite the methods being relatively similar. One of the limitations of conducting this sort of experiment *in vitro* is that it is difficult to replicate the biologic dynamics of the periodontal ligament and the impact it has on the position of teeth during an enamel reduction procedure. The silicone used to hold the teeth in place and replicate a periodontal ligament may fatigue and the mounted teeth may become progressively loose making it hard to know how much pressure to place when completing the IPR. When using an interproximal measuring gauge to determine the amount of reduction completed, as was the case in these two studies, conditions must be made as close to an *in vivo* setting as possible. An alternative would be to use electronic calipers to measure the widths of teeth before and after IPR procedures in an attempt to assess the amount of IPR completed.

Another limitation is that there is no tongue, cheeks and other patient factors to consider. It may be more difficult to complete IPR in the posterior aspect of the mouth with the influence of the soft tissues. Despite the fact that extracted premolar teeth were used in one study and extracted lower incisors in the other doesn't give an indication of differences in posterior versus anterior tooth reduction but rather shows the most commonly extracted intact teeth readily available for research.

The paper by Johner et al[20] used a 3-D laser scanner before and after reduction and superimposed the images to assess the amount of reduction completed. They scanned extracted premolar teeth before and after IPR using a 3-dimensional laser scanner to produce STL files of the sample. Reduction was assessed per tooth surface. The teeth involved were sprayed with a Pico Scan Spray in order to prevent reflections in the scan progress. The concern when making measurements of 0.01 mm with this technique is that the spray compound may interfere with the actual micro-structure of enamel and provide misleading results. Also, varying results may be seen if it was not distributed in an even thickness across all tooth samples.

Both studies considered the O-Drive D30 and despite some evidence to suggest it is more aggressive in conducting interproximal enamel it still holds its own merit as being the system to produce the smoothest enamel surface. The oscillating segmented disk is the most effective and safest technique for IPR. When followed by polishing with fine and ultrafine Sof-Lex discs it has been shown to result in enamel surfaces that are smoother and less likely to retain plaque than untreated enamel surfaces in 90% of cases[15].

A clinical setting is the ideal situation to assess the accuracy of enamel reduction as this would include the patient comfort, challenges in accessing contact points in different parts of the mouth, and the influence of a genuine periodontal ligament. Scanning of the interproximal contact points may be difficult unless a system is devised that can individually remove teeth from an arch for assessment in a digital setting.

To date no study has evaluated the accuracy of IPR by means of quantification in an *in vivo* setting.

2.5 The Periodontium

Even though IPR is completed on the coronal aspect of teeth the underlying supporting structure of the periodontium should be considered for adverse changes once reduced teeth have been reproximated. With this in mind there is no evidence to suggest an increased incidence of periodontal disease after re-approximation of reduced teeth, even though the space between teeth is decreased. In fact, it has been shown that the narrower the interproximal bone is, the better it resists periodontal disease[75]. Bishara has expressed concern that as the roots of teeth become closer after IPR there may be an acceleration of periodontal tissue breakdown of the thin interdental alveolar bone[76]. However this is unlikely and is contraindicated by some reports on the long term appearance of the osseous crest after stripping[46,77]. Boese[46] compared forty patients radiographs taken between four and nine years post-treatment involving IPR and found no significant differences in alveolar crest height or loss of interdental bone. Other *in vivo* studies have established that patients who have received IPR as part of their orthodontic treatment have good periodontal health[77,78]. These findings are supported by a 10 year follow up by Zachrisson[19].

2.6 Interproximal Reduction Armamentarium and Techniques

Treatment planning is of the utmost importance as IPR is an irreversible procedure. It is important to review the teeth to be reduced on a model or photographically before commencing and ensure adequate de-rotation has been completed prior to commencing. Only after alignment can IPR be accurately achieved without iatrogenic damage to adjacent teeth or soft tissues[79]. IPR can be completed with a range of techniques including rotary or oscillating discs, abrasive strips, and diamond or tungsten carbide burs. Stainless steel strips are popular and can be hand held, placed in a strip holder, or inserted into a contra-angle handpiece with a reciprocating action. They can have a fine, medium or coarse grit, on either one or both sides of the strip, as well as being perforated to aid removal of debris. They are beneficial even when a bur or disc is planned to be used on a non-rotated tooth to help open the contact point for ease of placement of the cutting instrument. Also, they can be used to polish enamel surfaces that have been reduced with coarse cutting instruments. Using proper techniques will help avoid introducing irregularity in the anatomy of a tooth which may make oral hygiene practices difficult.

There are several different techniques for undertaking IPR proposed in the literature[4,15,18,47]. The system described by Zachrisson[18] incorporates the use of rotary discs performed at the beginning of treatment but after the initial levelling and aligning stages. A 4-handed approach is used with the assistant keeping the patients tongue away with a mouth mirror, and at the same time blowing cold air on the tooth being reduced. Access is improved with the use of an Elliot anterior straight separator. Perforated diamond coated double sided stripping discs are used with extra fine diamond grit of 0.1 mm thick. Discs are available in varying grits on either one or both sides but also varying thicknesses. A single sided disc helps break the initial contact point and keeps the reduction to a single tooth at a time if desired. The motor is run at medium speed or about 30,000 rpm. A clear disc guard is placed to protect the adjacent soft tissues when using a rotating disc, however they can reduce visibility. An initial measurement should be made using a thickness gauge with the thought in mind that polishing will also remove a degree of tooth structure. Round or triangular diamond burs can then be used to round off any irregularities left on the enamel surface. Polishing is completed with Sof-Lex discs of a fine grit.

Air-rotor stripping is advocated by Chudasama and Sheridan who claim that ARS can create substantially more space than is usually obtained by conventional IPR procedures[4]. The smallest increment is approximately 0.3-0.4 mm per contact point with a diamond needle tip bur. Air-rotor driven burs and discs can be difficult to control precisely given that high speed motors run at speeds up to 200,000 rpm and slow speed motors run between 5000-20000 rpm. It can be difficult to be conservative using burs and risks of leaving a stepped and uneven surface are high. Placement of an elastic module will give an initial separation of the contact points aiding bur placement. The degree of separation must be measured on removal of the module and incorporated into the overall measurement of reduction. The placement of tooth separators may inadvertently come with pain or discomfort which can affect chewing, social life, school work and sleeping[80]. The IPR site is created by placing the bur beneath the contact point and moving it occlusally with light force. The bur can then be moved in a bucco-lingual direction until the amount of space desired has been created. Safe-Tipped air-rotor driven burs are available with 'deactivated' points to prevent creating ridges in the enamel. After the initial reduction a No. 699L tapered fissure carbide bur or medium to fine grit diamond bur contours the proximal surfaces. This is followed by even finer diamond burs and Sof-Lex discs to leave the enamel potentially smoother than unaltered enamel. Finally a fine abrasive strip coated with 35% phosphoric acid is used to briefly polish the proximal surfaces followed by thorough washing. This can further smooth the enamel after polishing with burs and discs. They advise the prescription of a fluoride rinse to aid remineralisation of the reduced surfaces.

Of recent years the use of oscillating systems has gained popularity. A study by Danesh et al[11] showed that the oscillating systems give the smoothest enamel surface after polishing compared to air-rotor and hand polishing strips. The oscillating system is thought to be safer than rotary discs or burs to the soft tissues and adjacent teeth. The oscillating motion is superior to rotary movement as binding or jamming in the interproximal contact point is minimized and accidental rotation into the adjacent hard or soft tissue is less likely to occur. However vibrations are generally felt by the patient with these systems. The Kavo O-drive system uses a 60° diamond disc that pivots at an angle of 30° and is operated from the occlusal to the cervical area under a water coolant. The Orthofile system uses mini-stripping bands mounted on an oscillating handpiece and move in a bucco-lingual direction. In a technique described by Zhong et al[15] a 3-step technique is used involving bulk reduction with an oscillating perforated diamond coated disc (<30µm grit size) and polishing with 2 Sof-Lex XT discs. This technique is regarded as being efficient only taking 2.2 minutes for each interproximal surface. The use of an oscillating diamond disc has been shown to result in no soft tissue lesions during stripping procedures apart from minor papillary incisions as the discs move cervically[74].

The rougher the surface to begin the more difficult it is to polish. Therefore the finer the stripping grit used, the easier and more successful polishing will be. Polishing is generally completed after reduction with fine abrasives such as Sof-Lex discs and strips. It has also been advocated that chemicals (acids) can be used for the stripping and or polishing stages too[4,12,13,67].

Care needs to be taken not to remove too much enamel from the proximal surfaces of teeth. As mentioned, standard values of enamel thickness of given teeth can be used as a guide. Standardised reduction gauges are an accurate means to help quantify the amount of IPR completed[81]. In circumstances when very small increments are aimed for removal the use of interproximal diamond strips alone will be sufficient. Considering that the amount of IPR conducted by one pass of a given cutting instrument is likely to be larger than the thickness of the instrument itself, thickness gauges are used as an accurate means to measuring the amount of IPR undertaken in a given procedure to within one tenth of a millimetre. Despite this radiographic analysis is essential to eliminate unique enamel patterns in particular individuals.

2.7 The Accuracy of Invisalign®

The process of IPR has extended to modern day orthodontic techniques such the Invisalign® system. It is popularized by all age groups and those who want to avoid the appearance of fixed appliances. The system was developed in 1997 and has become an accepted addition to traditional fixed orthodontic appliances consisting of transparent, semi-elastic polyurethane aligners that can correct tooth movements up to 0.3 mm with every two weeks of aligner use[82-85]. The clinical tooth malalignments are converted into the 3-D digital image or ClinCheck which shows a virtual image of the planned treatment outcome. The final result should correspond to this predicted final position. Aligners are produced from the planned ClinCheck in a series that allows systematic tooth movement. In addition attachments may be required to certain teeth to maximise a desired tooth movement. IPR is incorporated for planned orthodontic space gain. The accurate removal of enamel down to measurements as small as 0.1 mm is often required. Recent Invisalign® protocol improvements ensure that the timing of IPR is automatically staged when there is better access to interproximal contacts so that there is no significant overlap between teeth in an attempt to prevent damage of adjacent teeth[82].

It must be kept in mind that Invisalign® may not treat the most complex malocclusions as well as conventional appliances in certain circumstances. In a study by Djeu et al[86] it was determined that the strengths of Invisalign® are its ability to close spaces and correct anterior rotations and marginal ridge heights. It was deficient in its ability to correct large antero-posterior discrepancies and occlusal contacts. As Invisalign® is popular among adult patients who no longer have growth available for treatment, the use of IPR to resolve arch space discrepancies is a popular method in treatment planning.

In the first stage results of a study by Krieger et al[87] Invisalign® was analysed for its accuracy in the anterior tooth region. They compared pre and post-treatment plaster models to the initial and final ClinCheck and measured overbite, overjet, and dental midline shift. The study found minimal deviation and sufficient accuracy of the computer aided transfer and conversion of clinical tooth malalignments into a 3D digital image in ClinCheck. Despite this conclusion the final ClinCheck showed more corrections and better treatment results than those actually represented on the post-treatment model demonstrating the real situation. The differences were deemed clinically insignificant and could be altered with case refinement. Final results with a larger sample size by Krieger et al[88] state that the digital ClinCheck is a precise tool for treatment planning with regards to tooth movements in the anterior region. Overbite showed the greatest deviation between predicted and achieved tooth movements and overbite over-correction may be necessary. Vertical tooth movements tend to be achieved with less accuracy[87].

The main limitation of these studies and the Invisalign® Clincheck is that its 'ToothMeasure' tool and virtual measurement grid only measures to the nearest whole millimetre meaning if smaller measurements are desired they need to be visually defined to the nearest 0.5 mm or excluded all together.

2.8 Digital Study Models

Traditional plaster models have few limitations and their accuracy for measurements with a ruler or callipers is still regarded as a gold standard for orthodontic diagnosis[89-91]. The justification for the use of models is debateable with studies suggesting that treatment plans formulated with or without the use of study models have little difference[92,93]. Despite this digital models are gaining popularity due to the efficiency of access on the computer screen versus retrieval from storage, cost saving in storage and laboratory production fees, the accuracy and ease of measurement of tooth width, arch length and dental crowding, accurate and simple diagnostic setups for extraction and non-extraction cases, the elimination of transport and breakages constraints as files travel digitally, and easy consultation with colleagues throughout the world. The digital models need all the tooth surfaces and gingival contours to be visible in a clinically acceptable way[94].

Research published to date shows that the average discrepancy between measurements on digital and plaster models is low. A systematic review by Fleming et al[95] found an overall mean difference of linear measurements between plaster and digital models to be between 0.04-0.4 mm. Any statistically significant tooth size differences between studies have been found to be ambiguous and all studies have considered the differences clinically insignificant. The reliability and reproducibility of these computer models has been deemed satisfactory making them an acceptable alternative to plaster study models.

There are several ways to produce digital models. These include digitised photocopies and scans of plaster models, laser scanning of plaster models and alginate/silicone impressions, CBCT patient scans and CBCT scanning of alginate impressions or plaster models, stereophotogrammetry, and direct intra-oral scanning of the dentition[95,96].

An early method of model digitisation was introduced by Yen[97] who photocopied study casts and digitised key landmarks. A computer program was used to determine tooth widths and Bolton ratios however results showed a high potential for error and variability. Schirmer and Wiltshire[98] also concluded accurate measurements could not be made from photocopies and digitisation of dental casts. The main disadvantage was their 2D representation of a 3D object and differences in tooth inclination, deviation of tooth axes, crowded tooth positions, the curve of Spee, and the convex structure of teeth.

The validity of laser surface scanning of plaster models produced from alginate or polyvinylsiloxane impressions has been researched with no significant difference found when assessing overjet, overbite and arch length linear measurements for space analysis on 3D digital models or plaster models[21-27]. However Zilberman et al[27] stated that digital models are an acceptable option for clinical practice but might not be acceptable for research. Rheude et al[89] found that there were statistically significant differences in diagnostic characteristics between plaster and electronic models however the changes shown were minor and believed to be clinically insignificant. Also, The American Board of Orthodontics score and peer assessment rating (PAR) score have been deemed valid when assessed from digital 3D models[99-101]. Mesio-distal tooth width measurements have been analysed with minor mean differences (0.01-0.3 mm) from plaster to digital models created with laser scanners[24,102-104]. Digital models have shown a high degree of accuracy[22] and much of the error lies in measurement technique relating to point identification rather than being a problem of the software or measuring device[95]. Diagnosis and treatment planning decisions are not altered when using plaster or 3D digital models as a diagnostic aid and are not deemed a compromised option for orthodontic diagnosis and treatment planning[25,105].

Digital models created from CBCT scans appear to be as accurate as digital models obtained by laser scanning of plaster models for the measurement of overbite, overjet, and crowding[96]. Also, digital 3D models can be created by CBCT scanning of alginate impressions or plaster models. This technique has been found to be accurate enough for linear intra-arch measurements and the index of complexity, outcome, and need score[106-109]. However De Waard et al[110] found that measurements made directly on CBCT images are not as accurate as measurements made of digital models generated from CT scans of alginate impressions.

The system of stereophotogrammetry involves the use of stereo pairs of video cameras which are connected to a computer with coloured illumination to record study models in a digital format. Measurements off these digital models has been shown to be accurate when compared to direct measurement of study casts with differences ranging from 0.07-0.21 mm[111] and 0.1-0.48 mm[112]. These differences were not deemed to be clinically insignificant.

Research of the use of intra-oral scanners is limited, however digital models made with an intra-oral scanner are considered valid and reproducible. The ‘3M ESPE Lava Chair-side Oral Scanner’ has been registered and analysed producing valid, reliable, and reproducible linear measurements[113,114]. Also the iOC intraoral scanner has been determined clinically acceptable in terms of accuracy and excellent in its reliability and reproducibility when making measurements of digital study models compared to traditional stone casts[115]. The use of a direct intra-oral scanner eliminates the risk of impression distortion or dehydration, as well as pulls, tears and bubbles forming in the impression material.

2.9 Overview

The concept of IPR has evolved over time and relates back to the perception that humans naturally wear interproximal enamel surfaces to avoid dental arch crowding. The incorporation of IPR into routine treatment plans now extends to tooth size and inter-arch size discrepancies, stability post-orthodontics, and to give a more aesthetically pleasing tooth shape and gingival contour. IPR is a useful technique to correct arch length discrepancies and improve inter-occlusal relationships without the need for extraction. Variations exist between different teeth in terms of enamel thickness and this must be appreciated when considering IPR as part of a patient's management. It is best to remove only the bare minimum and attempt to re-contour the tooth shape to allow good approximation between contact points. Varying depths to which enamel can be reduced have been explored with the most widely accepted recommendations published by Fillion[65].

Several techniques have been proposed to complete IPR supported by clinical and scientific evidence for their existence. It has been suggested that abrasive strips produce deep furrows and scratches that cannot be removed by polishing afterwards[55]. These microscopic changes have the potential to promote the adherence of bacterial biofilms and increase the risk of dental caries development. Recent studies show that with adequate polishing enamel surface can be smoothed significantly and left potentially smoother than untreated enamel[11-15]. The rougher the surface to begin the more difficult it is to polish. Therefore the finer the grit used, the easier and more successful polishing will be. The most effective and safest technique for IPR uses perforated diamond coated discs with <30µm grain size for the initial reduction, followed by polishing with fine and ultrafine Sof-Lex discs. This results in enamel surfaces that are smoother and less likely to retain plaque than untreated enamel surfaces in 90% of cases[15]. The risk of developing dental caries after IPR has been extensively investigated and results show that there is no increased risk[10,16-19]. Periodontal health is also unaffected[19,46,77,78]. Evidence for and against the incorporation of acid etchant into the polishing stages of IPR is available. If an acid etchant is used as part of the polishing process in an attempt to maximise smoothness, fluoride should be considered to enhance the remineralisation potential of the enamel surface.

Digital models have the potential to show diagnostic set-ups with IPR as part of the treatment plan. In general 3-D digital models have been shown to be accurate in comparison to plaster models for linear measurements and an effective means for treatment planning[21-27]. The Invisalign® system, which incorporates a digital model, has been shown to be accurate when comparing proposed treatment versus treatment achieved[87,88]. This implies that the transfer of the PVS or intra-oral scans into the 3-D ClinCheck is accurate and such accurate measurements should be able to be taken from this data. Despite this the ability to make accurate measurements less than 1 mm, which is desirable for IPR, is limited in this system. Quantitative analysis of IPR is very limited and has only been inspected in an *in vitro* setting[11,20]. To date no study has evaluated the accuracy of IPR by means of quantification in an *in vivo* setting using digitally scanned data.

2.10 Significance

IPR demonstrates an alternative treatment option for orthodontic space gain in borderline extraction cases. Accurate IPR is essential to achieve proposed treatment objectives and is becoming more frequently desired with the increased popularity of digitally determined treatment plans. However there is currently limited evidence to support that it is an accurate technique to use. This review has identified two *in vitro* studies that provide a true quantitative analysis of enamel reduction. Limitations exist in extrapolating such results to a real life clinically setting. For this reason future studies are needed to evaluate the accuracy of IPR by means of quantification in an *in vivo* setting. The use of the Invisalign® system and 3-D digital models may aid the collection of data and the interpretation of the level of accuracy of IPR in a real patient setting.

2.11 Hypothesis

The null hypothesis for this study states that there is no statistically significant difference when comparing:

- Proposed and actual amounts of IPR completed (accuracy).
- The accuracy of IPR within and between upper and lower dental arches.
- The accuracy of IPR within and between posterior and anterior arch segments.

CHAPTER 3: MATERIALS AND METHOD

Low or negligible risk human research ethics approval was granted from the James Cook University Ethics Committee (approval number H5315) for the project to be conducted (Appendix 8.1).

3.1 Sample

Once the project was granted approval by the ethics committee, the next 20 patients who had IPR completed in either one or both arches that required a case refinement impression post-IPR for mid-course correction were included. This provided a total of 40 possible arches for the study when including upper and lower arches. Of these 40 arches 12 had no IPR completed leaving a total of 28 arches to analyse. Two of these arches had IPR completed at two separate locations allowing two actual records for assessment within the one arch. This provided a total of 30 arches with pre and post-IPR digital study models available.

Three-dimensional digital study models were collected from Clinchecks of active Invisalign® patients. Inclusion criteria required cases that had IPR as part of the desired treatment plan, which had both digital study models of pre and post IPR available. To determine the level of accuracy of IPR, the initial pre-op ClinCheck for treatment planning that came with a listed amount of IPR to be completed at each contact point, provided a proposed amount of IPR. A second Clincheck taken at case refinement as a mid-course correction provided a 3-dimensional model after IPR had been completed from which the actual amount of IPR can be determined. The actual amount of IPR was then compared to the proposed amount of IPR and a level of accuracy was determined.

The digital study models were then extracted in STL (stereolithography) format which is inherent to computer aided design software and 3-dimensional systems. All models were supplied in a de-identified form labelled 100-119, U for upper arch, L for lower arch, A for pre-IPR model, and B for post-IPR model. For example 115AU is file number 115 pre-IPR for the upper arch.

All cases were gathered from a single private specialist orthodontist in Brisbane Australia who is a frequent user of Invisalign®. All impressions were taken using Imprint 3 polyvinylsiloxane putty and light body impression material. All IPR was completed using perforated hand strips if 0.2 mm or less was proposed, or a combination of rigid or flexible discs if greater than 0.2 mm was proposed. The quantity of IPR was measured using a standard IPR measuring gauge.

The files were imported into Geomagic Control 2014.0.0.1660: 64 Bit Edition Geomagic Incorporated, digital design software capable of measuring to one thousandths of a millimetre if desired. The models were manipulated using the programs panning, rotation, and zoom features and viewed on a 22 inch computer screen with a resolution of 1920 x 1080 pixels and 32-bit colour. A standard hard-wired laser computer mouse was used to manipulate the models and accurately identify points.

Measurement of the maximum mesio-distal width of each tooth was completed using the Analysis-Measure-Distance tool from the software. For precision of the measurements at the interdental contact point each tooth was individually selected and then isolated for measurement of its maximum mesio-distal width (Figure 3). The measurements were recorded from the ‘X’ axis to eliminate change in length between the two points due to a variation in the point’s vertical height. A discrepancy in vertical height between the two points increases the mesio-distal length.

The maximum mesio-distal width of the teeth involved off the pre-op and case refinement ClinChecks were measured to the nearest micrometer.

To assess the level of consistency between the pre and post-IPR models, a given tooth (typically a molar) not involved in IPR within each arch had its maximum mesio-distal width measured on the initial pre-op Clincheck and case refinement study model. This acted as a point of reference for control and to validate the data sample. The order of measurements was completed randomly. An interval of 2 weeks was set between measurements of pre and post IPR models to remove any bias. Once the sample had been validated measurements were commenced on all teeth involved in IPR.

In a given arch, the maximum mesio-distal width of the teeth was measured either side of the contact point that underwent IPR. This means that when one contact point was involved two teeth were measured. If four contact points were involved then five teeth were measured. IPR was never continued to the distal surface of the last tooth within an arch and this acted as a stable point to stop the measurements. All measurements were completed by the one examiner (MB/Assessor A). As with data validation, there was a two week gap between measurements of the pre and post IPR data to remove any bias.

To assess intra-examiner reliability the digital models were then assigned a new de-identified number using the same labelling sequence for the initial measurements so that the examiner was blinded. All measurements were repeated by the same examiner two weeks later with the same protocol of a two week gap between measurements of the pre and post IPR data.

To examine the reproducibility of the measuring technique 20 arches were randomly selected and measured by a second examiner (SA/Assessor B).

The total arch measurements used for the inter-examiner and intra-examiner reliability assessment were divided by the number of teeth measured to produce an average tooth width per arch for assessment. Each arch measured had IPR completed at a different number of contact points ranging from one to seven contact points. For this reason the totals recorded were then divided by the number of tooth surfaces involved to produce an average amount of IPR completed per tooth surface between each arch.

Proposed IPR for a given arch was calculated by adding the amounts of IPR planned to be completed on the initial Clincheck. The difference of cumulative maximum widths of teeth between pre and post IPR showed the actual amount of IPR. Finally the proposed amount of IPR was subtracted from the actual amount of IPR and the difference from zero determined the level of accuracy of IPR in a given arch.

For IPR to be completed with absolute accuracy there would be no difference between the actual and proposed amounts of IPR. If IPR was over-achieved a positive value is produced. If IPR is under-achieved a negative value is produced (Figure 4).

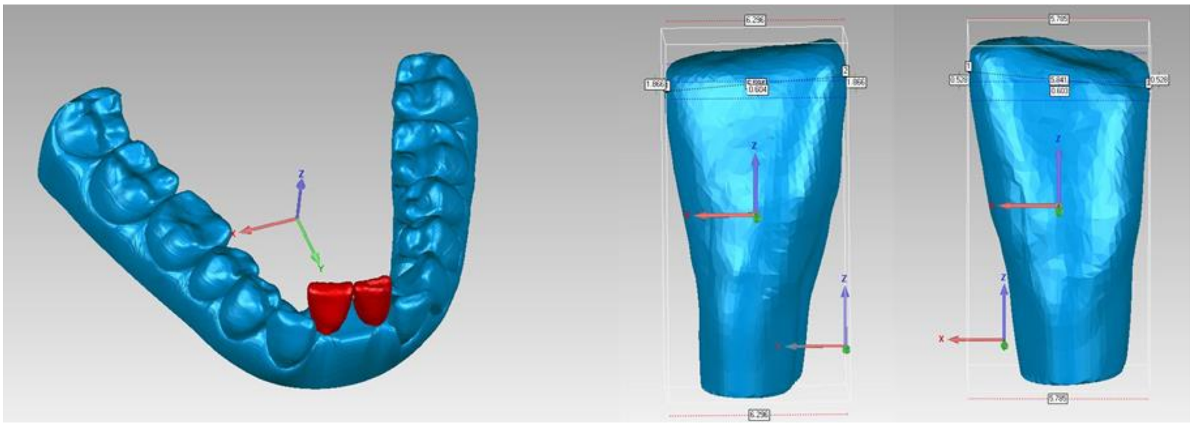

Figure 3: Image demonstrates the process of tooth selection (in red) on the left hand side. The teeth were individually isolated and measurements completed of the maximum mesio-distal width on the right hand side.

Screenshot from Geomagic Control software (Rock Hill, USA).

ACCURACY = **ACTUAL IPR** minus **PROPOSED IPR**.

ACTUAL IPR = Addition of the maximum mesio-distal widths of the teeth planned to have IPR completed minus the addition of the maximum mesio-distal widths of the same teeth once they have undergone IPR in a given arch.

PROPOSED IPR = Addition of the amounts of IPR to be completed on the initial Clincheck in a given arch.

ABSOLUTE ACCURACY: ACTUAL IPR minus PROPOSED IPR = 0

IPR OVER-ACHIEVED: ACTUAL IPR minus PROPOSED IPR >0 (+ve value)

IPR UNDER-ACHIEVED: ACTUAL IPR minus PROPOSED IPR <0 (-ve value)

Figure 4: Figure shows the measurement definitions used.

3.2 Method Error

The sources of error inherent in this study are two folds: operator error and technical error. Operator error could result from the inconsistency of the operator in identifying the maximum mesio-distal dimension on each tooth required to be measured. In addition errors may also occur while recording, transferring and utilizing the data obtained.

On the other hand, technical errors may be contributed by the inaccuracy or reproducibility of the 3-dimensional images when being scanned from the polyvinylsiloxane impression by the Invisalign laser scanner. If the STL file produced after scanning is not exactly the same scale from the pre-IPR to the post-IPR scan, the error will be introduced into the results.

The reproducibility and error of the method in this study were tested by repeating all measurements twice. To strengthen the accuracy of these measurements the data were blinded between each set of measurements as not to introduce any bias. The measuring technique was also compared by two independent assessors to check for consistency or variability of the measuring technique.

3.3 Statistical Analyses

All measurements were recorded in Excel (version 2010; Microsoft, Redmond, Wash). Statistical analyses were performed using Graphpad Prism 6.04 (GraphPad Software, La Jolla California USA, www.graphpad.com).

Data was tested for normality using the D'Agostino-Pearson omnibus K2 normality test. Where applicable parametric tests were used otherwise the non-parametric equivalent was conducted.

3.3.1 Validation of Data

To validate the data set before measurements could be undertaken the width of a given tooth (typically a molar) not involved in IPR within each arch that is to be assessed had its mesio-distal width measured on the initial pre-op Clincheck and case refinement Clincheck to act as a point of reference for control. The order of measurements was completed randomly to check for consistency between the models and to validate the data sample. This was completed for each of the 30 arches.

A Wilcoxon matched pairs signed rank test was conducted on these pre-IPR and post-IPR measurements.

3.3.2 Inter-Examiner Reliability

An unpaired *t* test was used to compare the difference between parameters of 20 randomly chosen arches measured by different operators, known as the initial assessor 'MB' and a second assessor 'SA', to test consistency of the measuring method.

3.3.3 Intra-Examiner Reliability

An unpaired *t* test was used to compare the difference between parameters of 20 randomly chosen arches measured two weeks apart to verify the intra-examiner reproducibility.

3.3.4 Overall Accuracy: Proposed versus Actual IPR

An unpaired *t* test was used to compare the difference between parameters of the proposed and actual values.

3.3.5 Accuracy: Upper and Lower Arch

A Mann Whitney U test was used to compare the difference between parameters of the proposed and actual values within the upper arch, and an unpaired *t* test was used to compare the difference between parameters of the proposed and actual values within the lower arch.

An unpaired *t* test was used to compare the difference between parameters of upper and lower accuracy levels.

3.3.6 Accuracy: Posterior and Anterior Segment

A Mann Whitney U test was used to compare the difference between parameters of the proposed and actual values within the posterior segment, and an unpaired *t* test was used to compare the difference between parameters of the proposed and actual values within the anterior segment.

A Mann Whitney U test was used to compare the difference between parameters of posterior and anterior accuracy levels.

CHAPTER 4: RESULTS

The results are presented in tables and figures and are specific to each section that was analysed.

4.1 Validation

Table 3 demonstrated that there was no significant difference between the maximum width of the same reference tooth measured on 30 pre and post IPR models (p=0.640).

This verified the data sample as being consistent between the pre and post IPR models and was suitable for use in the study.

4.1.1 Data Validation

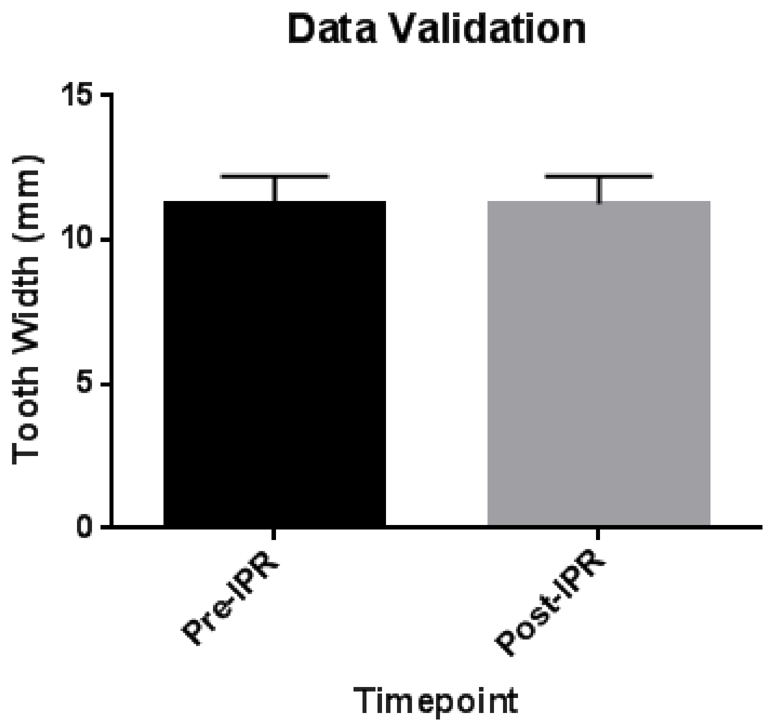

Figure 5: Results of Data Validation

	Mean	Std. Dev.	Significance
Pre-IPR	11.25	11.25	P=0.640
Post-IPR	0.968	0.967	

Table 3: Data Validation mean, SD, significance level

4.2 Reliability Tests

Table 4 demonstrated that there was no significant difference between the sets of measurements produced by the two assessors (p=0.999).

Table 5 demonstrated that there was no significant difference between the two sets of measurements produced by the main assessor (p=0.994).

This determined that the measuring technique is reproducible and reliable for use in the study.

4.2.1 Inter-Examiner Reliability

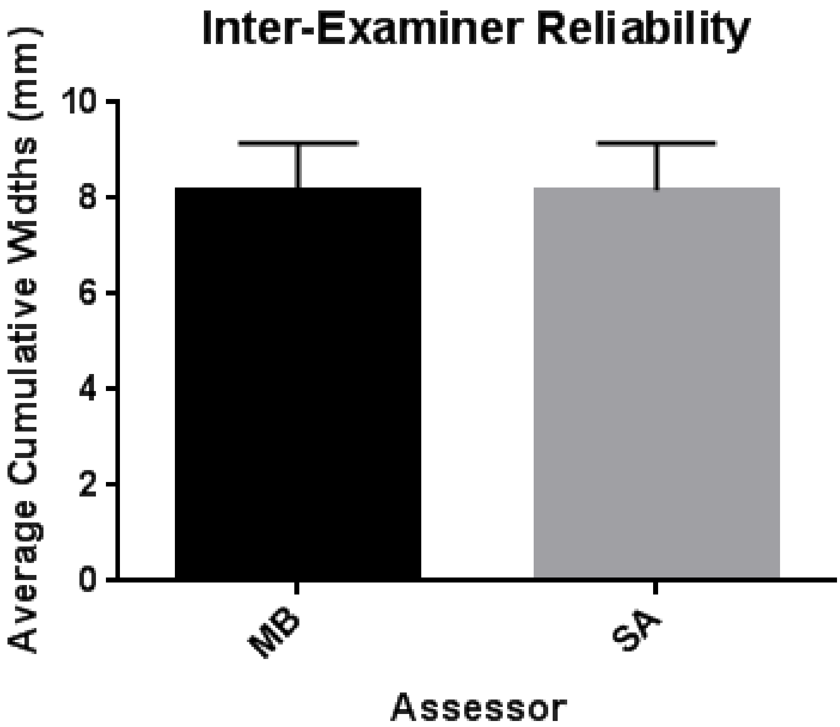

Figure 6: Results of inter-examiner reliability test

	Mean	Std. Dev.	Significance
MB	8.171	0.980	P=0.999
SA	8.171	0.980	

Table 4: Inter-examiner reliability mean, SD, significance level

4.2.2 Intra-Examiner Reliability

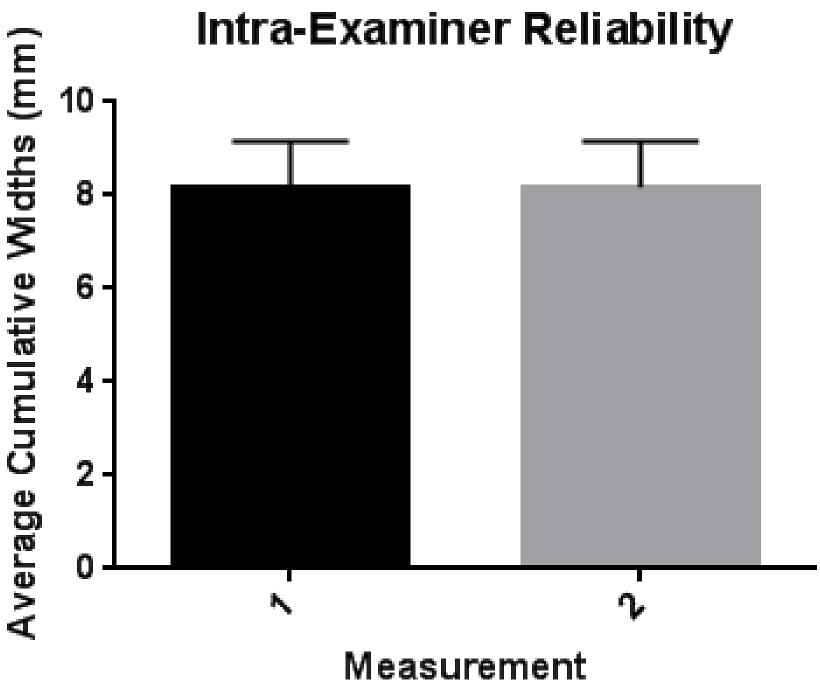

Figure 7: Results of intra-examiner reliability test

	Mean	Std. Dev.	Significance
1	8.171	0.980	P=0.994
2	8.169	0.982	

Table 5: Intra-examiner reliability mean, SD, significance level

4.3 Accuracy Tests

Table 6 demonstrated that there was a significant difference between the proposed and actual amounts of IPR per tooth surface for all 30 arches ($p<0.0001$). IPR per tooth surface was ineffective by 55.9% overall.

There were similar levels of ineffectiveness within the upper (60.5%) and lower arches (49.4%) presented in Tables 7 and 8, and within posterior (42.3%) and anterior (58.6%) segments presented in Table 10 and 11. There were equal numbers of upper and lower arches (15 each) however uneven number of posterior (22) and anterior (29) segments.

There was no significant difference in accuracy of IPR per tooth surface between the upper and lower arches (Table 9) or between the posterior and anterior segments (Table 12).

4.3.1 Overall Accuracy: Proposed versus Actual IPR

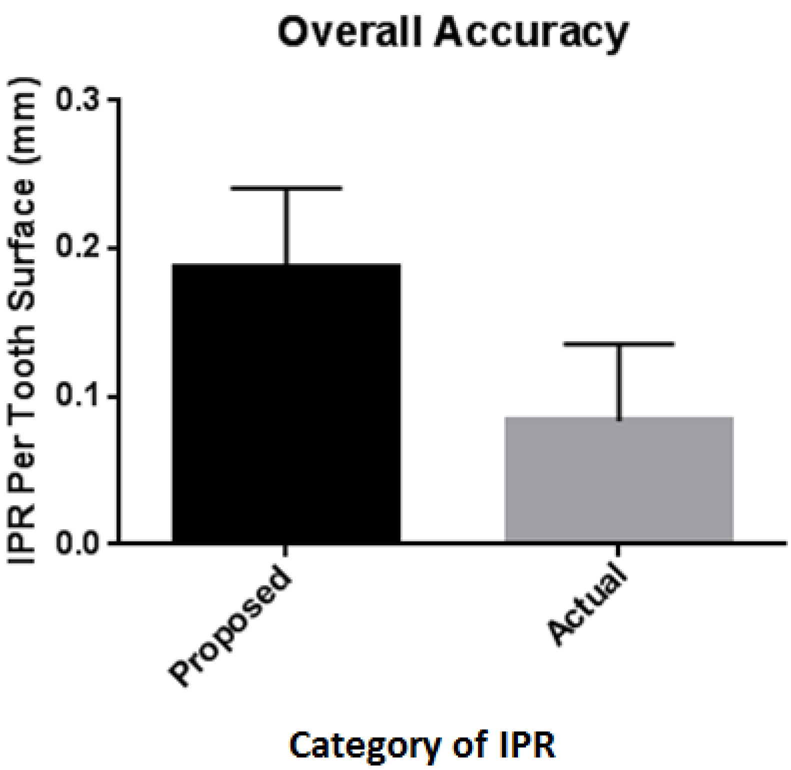

Figure 8: Overall accuracy: comparison of proposed and actual IPR

	Mean	Std. Dev.	Difference Between Means	IPR Accuracy Per Surface	Significance
Proposed	0.188	0.053	-0.105	-55.9%	p<0.0001 (t=7.668)
Actual	0.083	0.052			

Table 6: Results of Overall Accuracy assessment

4.3.2 Accuracy: Upper and Lower Arch

4.3.2.1 Accuracy: Upper Arch

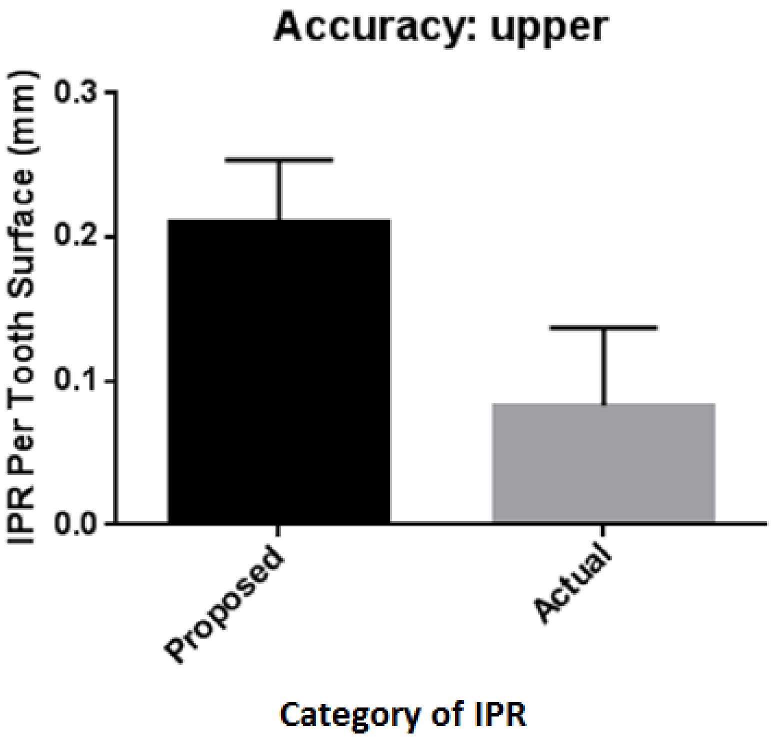

Figure 9: Accuracy in Upper Arch: comparison of proposed and actual IPR

	Mean	Std. Dev.	Difference Between Means	IPR Accuracy Per Surface	Significance
Proposed	0.210	0.044	-0.127	-60.5%	p<0.0001*
Actual	0.083	0.054			

*p value calculated with Mann Whitney U test

Table 7: Results of Upper Arch Accuracy assessment

4.3.2.2 Accuracy: Lower Arch

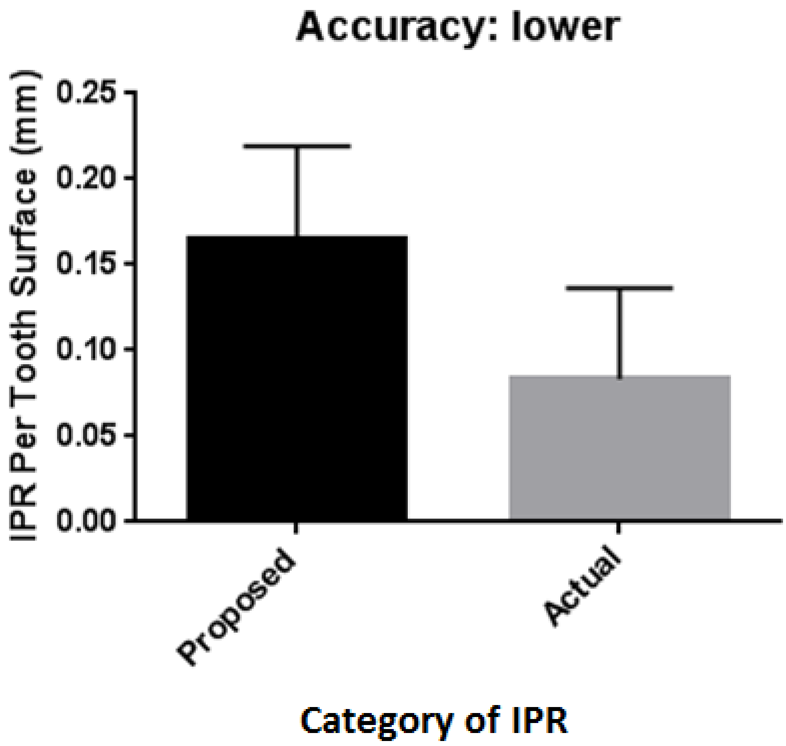

Figure 10: Accuracy in Lower Arch: comparison of proposed and actual IPR

	Mean	Std. Dev.	Difference Between Means	IPR Accuracy Per Surface	Significance
Proposed	0.166	0.054	-0.082	-49.4%	p<0.0002 (t=4.216)
Actual	0.083	0.053			

Table 8: Results of Lower Arch Accuracy assessment

4.3.2.3 Accuracy: Upper versus Lower Arch

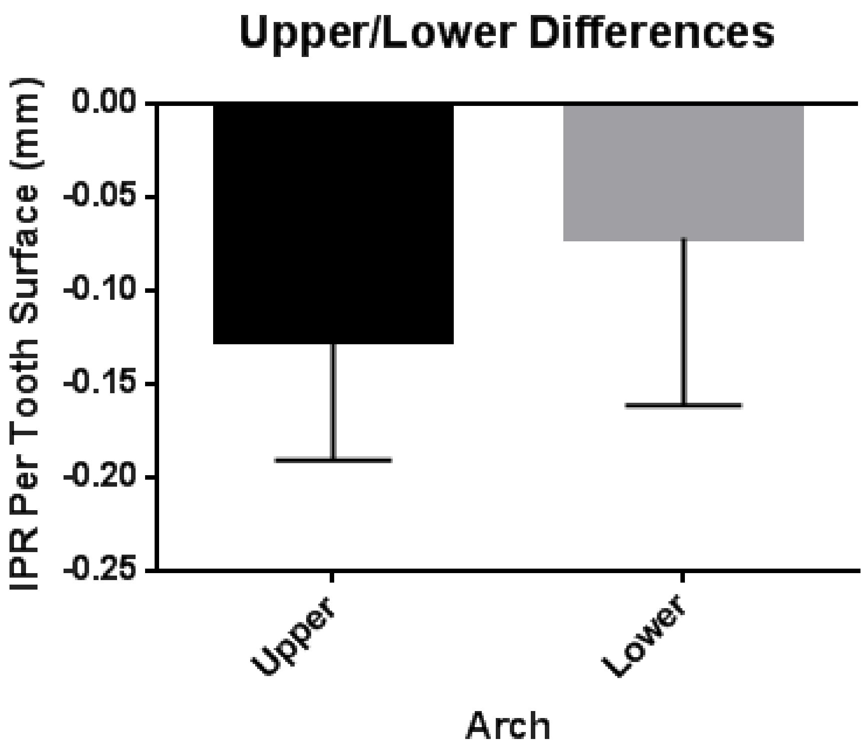

Figure 11: Assessment of accuracy between upper and lower arches

	Mean	Std. Dev.	Significance
Upper	-0.127	0.064	p<0.062
Lower	-0.072	0.090	(t=1.948)

Table 9: Results of accuracy between upper and lower arches

4.3.3 Accuracy: Posterior and Anterior Segments

4.3.3.1 Accuracy: Posterior Segment

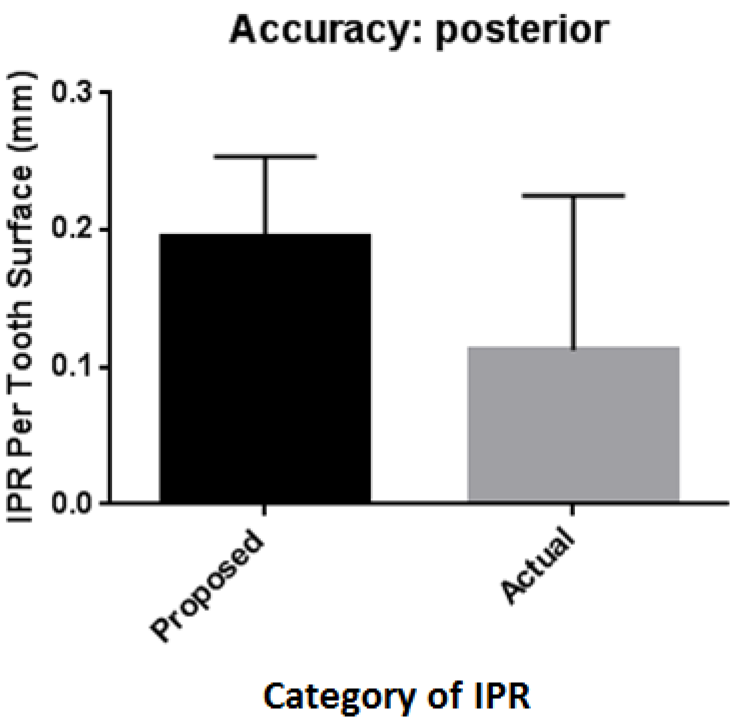

Figure 12: Accuracy in Posterior Segment: comparison of proposed and actual IPR

	Mean	Std. Dev.	Difference Between Means	IPR Accuracy Per Surface	Significance
Proposed	0.196	0.058	-0.083	-42.3%	p<0.0014*
Actual	0.112	0.113			

*p value calculated with Mann Whitney U test

Table 10: Results of Posterior Segment accuracy assessment

4.3.3.2 Accuracy: Anterior Segment

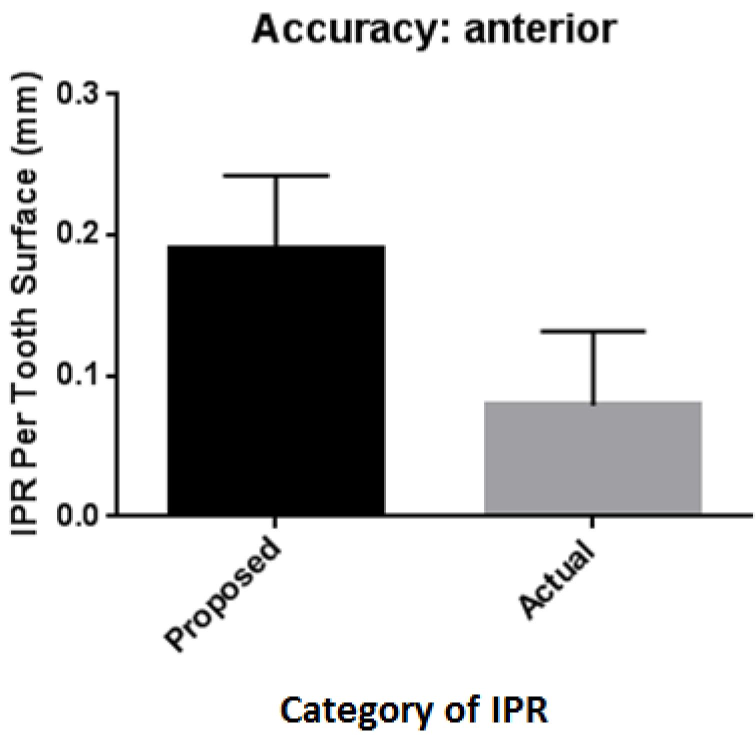

Figure 13: Accuracy in Anterior Segment: comparison of proposed and actual IPR

	Mean	Std. Dev.	Difference Between Means	IPR Accuracy Per Surface	Significance
Proposed	0.191	0.051	-0.112	-58.6%	p<0.0001 (t=8.192)
Actual	0.079	0.053			

Table 11: Results of Posterior Segment accuracy assessment

4.3.3.3 Accuracy: Posterior versus Anterior Segment

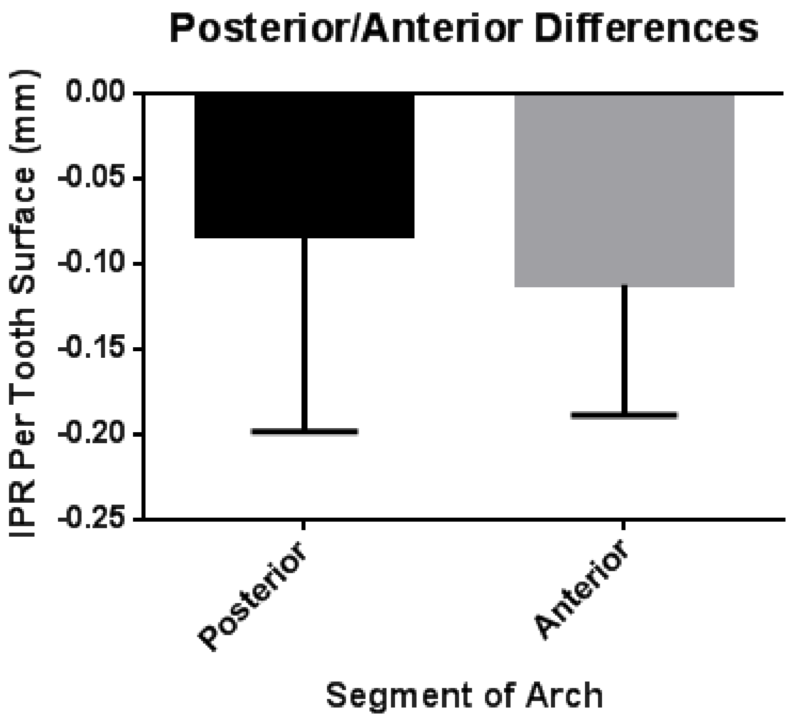

Figure 14: Assessment of accuracy between posterior and anterior segments

	Mean	Std. Dev.	Significance
Posterior	-0.083	0.115	p<0.352*
Anterior	-0.112	0.077	

*p value calculated with Mann Whitney U test

Table 12: Results of accuracy between posterior and anterior segments

CHAPTER 5: DISCUSSION

This study assessed the accuracy of inter-proximal enamel reduction using 3D study models in an *in vivo* setting. The results indicate that IPR might not be completed with a high degree of accuracy and that the amount completed is generally much smaller than what is trying to be achieved. This is true when completing IPR in both the upper or lower arch, and in either the posterior or anterior arch segment. The null hypothesis is rejected for the overall accuracy, the accuracy of IPR within the upper and within the lower arches, and within posterior and within anterior segments. There was no significant difference between the upper and lower arches, or between posterior or anterior segments.

Overall IPR was deficient by 55.9% per tooth surface in the sample assessed. On average 0.188 mm of IPR was aimed to be completed per tooth surface however only 0.083 mm was actually achieved showing an under-achievement on average of 0.105 mm per tooth surface which is statistically significant. Not only is there a statistically significant difference between the proposed and actual amounts of IPR a deficiency of more than 50% is deemed clinically significant. When IPR is incorporated as a specific treatment modality with a set amount it is important that it is completed as close as possible to the value set. As the percentage amount per surface of IPR actually achieved starts to differ from what is desired the likelihood of reaching the initial treatment goal starts to decrease. For this reason IPR must be completed with a high degree of accuracy if it is to be incorporated into a treatment plan.

Both upper and lower arches showed a significant difference between their actual and proposed IPR amount per tooth surface. IPR was less accurate in the upper arch with an average 60.5% under-achievement per tooth surface compared with the lower arch with an average 49.4% under-achievement. Both of these percentage figures have been deemed clinical significant. Despite this there was no significant difference in accuracy of IPR per tooth surface between the upper and lower arches (p=0.062). The higher level of ineffectiveness of IPR completed per tooth surface in the upper arch could have two possible explanations. First the upper arch showed a slightly higher proposed average amount of IPR per tooth surface (0.210 mm) compared with the lower arch (0.166 mm). The operator completing the IPR may subconsciously only reduce a particular conservative amount to prevent over reduction and adverse effects to the tooth. If this is true there would be a greater difference between proposed and actual amounts of IPR per tooth surface and subsequently IPR would be more ineffective in the upper arch compared to the lower arch. The second reason is that it may be more difficult for the operator to manipulate the IPR implement to the upper arch given the potential need for indirect visualisation of the tooth surfaces to be reduced. As mentioned the upper arch showed a slightly higher proposed average amount of IPR per tooth surface (0.210 mm) compared with the lower arch (0.166 mm). Despite this the same actual amount of IPR (0.083 mm) per tooth surface was achieved in both upper and lower arches. This verifies the first possible reason why there is a greater percentage inadequacy of IPR per tooth surface in the upper arch. Despite the consistency in the operator to complete the same amount of IPR per tooth surface it demonstrates the inability to reach the treatment goal of completing an accurate amount of IPR.

Similar to the findings observed in the upper and lower arches both posterior and anterior arch segments showed a significant difference between their actual and proposed IPR amount per tooth surface. IPR was less accurate in the anterior segment with an average 58.6% under-achievement per tooth surface compared with the posterior segment with an average 42.3% under-achievement. Once again such a high level of ineffective IPR is deemed clinically significant. Despite this there was no significant difference in accuracy of IPR per tooth surface between the posterior and anterior segments (p=0.352). The posterior and anterior segments had very similar average proposed amounts of IPR per tooth surface (0.196 mm and 0.191 mm respectively) however a much smaller amount of IPR per tooth surface was completed in the anterior segment (0.079 mm) compared with the posterior segment (0.112 mm). This may reflect the operators clinical judgement in trying to be conservative with the amount of reduction completed on anterior teeth as they generally have a smaller amount of enamel available to remove compared to thicker amounts of enamel available on posterior teeth. It may have been expected that less enamel per tooth surface would be removed in the posterior segment due to greater difficulty in accessing this area of the mouth however this was not the case. Once more an inability to reach the treatment goal of completing an accurate amount of IPR is observed.

IPR was completed per contact point however measured per tooth surface. The contact point between a canine and premolar tooth meant that half the IPR was aimed to be completed in the anterior segment and the other half in the posterior segment. If the IPR was not completed with an exact 50:50 ratio, for example if it was not completed in line with the long axis of the tooth and was skewed to one side, the proportion of IPR completed in the posterior or anterior segments would differ, ultimately influencing the accuracy in each segment.

It must also be mentioned that there was a slight difference in sample size between the posterior and anterior segments of the mouth. There were only twenty-two arches with IPR completed in the posterior segment compared to twenty-nine arches with IPR completed in the anterior segment which may influence the statistical outcome.

Danesh et al[11] found no difference between the amount of IPR completed and that what was aimed for except for the O-drive D30 system which removed significantly more enamel than desired. Quantification was assessed using a radiographic digital subtraction technique in which radiographs were taken before and after reduction and then digitised and analysed in Photoshop. The difficulty in using such a technique is that if the radiograph is not taken at true perpendicular axis to the mesio-distal axis of the tooth distortion is introduced into the image. Also as the experiment was conducted *in vitro* on extracted lower incisor teeth it is difficult to relate these findings of IPR accuracy to the study at hand.

The overall findings of this research project are consistent with those presented by Johner et al[20] in their *in vitro* IPR quantification study. They concluded that there were large variations in the amounts of stripped enamel however in most cases the amount of actual stripping was less than the intended amount no matter which reduction method used. They observed statistical significant differences at 0.1 mm of intended stripping for the hand-pulled method and at 0.4 mm of intended stripping for all methods.

Considering the results of this study demonstrate a generalised under-achievement of IPR per tooth surface it is important to consider the possible reasons why this may have occurred. One explanation is that as the IPR implement is passed through the contact point pressure on the teeth move them laterally into the periodontal ligament space. As the

Clinchecks used in the study were from cases in active treatment it would be expected that there would be a degree of mobility of the teeth involved due to the inflammatory process inherently associated with tooth movement. Also stretched periodontal fibres might move the teeth during or after the reduction procedure. The same thing may occur when checking the amount of reduction with a measuring gauge such that it appears to the operator that the correct amount of reduction has been achieved. It may be thought that using hand strips produce a greater amount of tooth displacement compared to motor driven or oscillating strips/discs. However Johner et al[20] found that the stripping technique is not a significant predictor of the actual amount of enamel reduction.

Danesh et al[11] mentioned that polishing after bulk reduction is completed will remove on average up to 0.02 mm of enamel. There was no mention as to whether the operator who conducted the IPR in this study polished after completing IPR. If not, this could be a possible contributing factor to the overall deficiency in IPR.

Accuracy was assessed between pre-op digital study models and those gained at case refinement after IPR was completed. There are numerous reasons why a Clincheck may not track accordingly to the digital treatment plan. However considering that the initial Clincheck is designed to produce an ideal final occlusal with IPR as part of the treatment sequence required, one of the reasons that a case refinement Clincheck was required at all may be that the Clincheck hadn't tracked as planned because insufficient IPR was completed. If IPR was inadequate there may not have been enough space between the teeth under the aligner to allow the desired tooth movements to be completed.

Naidu et al[115] suggested that when measuring tooth widths off virtual models the operator has no physical barrier to the placement of measurement points resulting in slightly larger digital values compared to stone casts. Cuperus et al[113] also found greater values when conducting measurements off digital models compared to physical models. If this finding is relevant to the study conducted here it is possible that the actual tooth widths measured would be slightly increased meaning that the overall difference recorded (accuracy) would be slightly over estimated and the percentage difference per surface is in fact slightly higher.

A limitation identified in the literature in accurately measuring mesio-distal tooth widths from contact point to contact point on either cast stone or digital study models is access to the interdental region. With any digital models there is always a small amount of missing data from the contact points which the computer is expected to calculate. Despite this one of the main advantages of using the method described in this project is that each tooth was able to be individually isolated for measurement of its mesio-distal width. This allowed for accurate measurement of the data sample which was confirmed by both intra and inter-examiner reliability tests which showed no significant difference between measurements.

Inaccuracy or reproducibility of the 3-dimensional images when being scanned from the polyvinylsiloxane impression by the Invisalign laser scanner is a potential source of error. If the STL file produced after scanning is not exactly the same scale from the pre-IPR to the post-IPR scan then error will be introduced into the results. To ensure there was no technical errors of the digital scans or errors in scaling of the pre-IPR and post-IPR models data validation was completed. Data validation produced the same mean tooth width measurements and a Wilcoxon matched pairs signed rank test confirmed that there was no significant difference between the data sets.

Considering that overall IPR was under-achieved by just over half of what was desired, the accuracy of IPR may be improved by keeping the same IPR procedure except completing the procedure on two separate occasions. Also this progressive approach to reduction may be appropriate as it has been suggested that reduction of smaller amounts of enamel is more predictable[4]. This would also prevent the risk of increasing intra-pulpal temperature and associated pulpitis if trying to remove too much enamel at once. Relying on IPR measuring gauges or using disks with predetermined thickness to assess the amount of IPR completed is likely to give an unsatisfactory result. Another option would be to follow the method described in this study. Determine accuracy by calculating a proposed and an actual cumulative tooth width using digital Vernier callipers intra-orally and adjust the amount of reduction accordingly if under-achieved.

Ideally this sort of experiment would be conducted on a much larger sample from numerous operators at multiple global locations to give a better understanding of the accuracy achieved with IPR. Although the study only aimed to assess accuracy of IPR the method could be adapted to also differentiate the accuracy between different reduction techniques.

CHAPTER 6: CONCLUSION

This study demonstrates the insufficiencies in modern IPR techniques which can be related to daily orthodontic clinical practice.

Overall IPR was deficient by 55.9% per tooth surface which is deemed to be of clinical significance. IPR cannot be completed with a high degree of accuracy and the amount completed is generally much smaller than what is trying to be achieved. This is true when completing IPR in both the upper or lower arch, and in either the posterior or anterior arch segments.

Clinicians should acknowledge the findings and critique their own technique of IPR accordingly to ensure the highest standard of treatment outcomes.

APPENDICIES

Appendix 1: Ethics Approval

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has been removed

Appendix 2: Data Validation

ID-Initial	A=Pre IPR	B=Post IPR
100U	10.439	10.443
101U	11.536	11.54
102U	10.934	10.929
103U	11.987	11.989
104Ui	11.044	11.039
105U	7.687	7.689
106U	10.838	10.836
112U	11.168	11.166
113Ui	10.313	10.317
113Uii	10.313	10.317
114U	11.545	11.543
116U	10.236	10.239
117U	10.651	10.651
118U	11.223	11.224
119U	11.477	11.479
101L	12.687	12.691
102L	10.76	10.765
103L	12.551	12.554
104Li	11.171	11.168
104Lii	11.171	11.168
105L	11.735	11.735
107L	12.068	12.066
108L	11.003	10.998
109L	11.575	11.577
110L	12.199	12.195
111L	11.177	11.174
114L	12.246	12.25
115L	11.087	11.092
118L	12.482	12.48
119L	12.272	12.269

Figure 15: Raw data used in data validation.

Appendix 3: Inter-Examiner Raw Data

ID-Initial	Assessor MB	Assessor SA
100UA	8.433	8.431
101UA	8.25	8.254
102UA	7.711	7.711
103UA	8.24	8.238
104UiA	7.767	7.767
105UA	10.383	10.38
106UA	7.076	7.077
112UA	7.449	7.447
113UiA	7.712	7.707
113UiiA	9.444	9.441
100UB	8.304	8.304
101UB	7.985	7.987
102UB	7.418	7.418
103UB	8.044	8.044
104UiB	7.739	7.739
105UB	10.283	10.284
106UB	6.984	6.985
112UB	7.296	7.294
113UiB	7.528	7.525
113UiiB	9.383	9.384

Figure 16: Raw data used to complete inter-examiner reliability test.

Appendix 4: Intra-Examiner Raw Data

ID-Initial	Measurement 1	Measurement 2
100UA	8.433	8.429
101UA	8.25	8.253
102UA	7.711	7.711
103UA	8.24	8.24
104UiA	7.767	7.767
105UA	10.383	10.383
106UA	7.076	7.075
112UA	7.449	7.447
113UiA	7.712	7.708
113UiiA	9.444	9.444
100UB	8.304	8.301
101UB	7.985	7.987
102UB	7.418	7.419
103UB	8.044	8.044
104UiB	7.739	7.738
105UB	10.283	10.283
106UB	6.984	6.948
112UB	7.296	7.295
113UiB	7.528	7.525
113UiiB	9.383	9.384

Figure 17: Raw data used to complete intra-examiner reliability test.

Appendix 5: Overall Accuracy Divided by Number of Tooth Surfaces

Combined Accuracy Data

ID-Initial	Proposed IPR/S	Actual IPR/S	Difference/S
100U	0.15	0.077	-0.072
101U	0.25	0.151	-0.099
102U	0.214	0.167	-0.047
103U	0.25	0.112	-0.138
104Ui	0.25	0.018	-0.233
104Uii			
105U	0.25	0.101	-0.149
106U	0.183	0.054	-0.13
107U			
108U			
109U			
110U			
111U			
112U	0.25	0.087	-0.163
113Ui	0.2	0.184	-0.016
113Uii	0.1	0.061	-0.04
114U	0.175	0.018	-0.157
115U			
116U	0.225	0.076	-0.149
117U	0.225	0.009	-0.216
118U	0.229	0.039	-0.19
119U	0.2	0.093	-0.107
100L			
101L	0.1	0.105	0.005
102L	0.1	0.169	0.069
103L	0.233	0.101	-0.133
104Li	0.1	0.016	-0.085
104Lii	0.1	0.023	0.078
105L	0.25	0.035	-0.216
106L			
107L	0.15	0.109	-0.038
108L	0.15	0.168	0.018
109L	0.143	0.06	-0.083
110L	0.229	0.096	-0.132
111L	0.15	0.028	-0.122
112L			
113Li			
113Lii			
114L	0.2	0.129	-0.072
115L	0.214	0.012	-0.203
116L			
117L			
118L	0.213	0.075	-0.138
119L	0.15	0.126	-0.025

Figure 18: Data used to calculate overall accuracy per tooth surface.

Appendix 6: Upper/Lower Accuracy Divided by Number of Tooth Surfaces

Upper Arch			
ID-Initial	Proposed IPR/S	Actual IPR/S	Difference/S
100U	0.15	0.077	-0.072
101U	0.25	0.151	-0.099
102U	0.214	0.167	-0.047
103U	0.25	0.112	-0.138
104Ui	0.25	0.018	-0.233
104Uii			
105U	0.25	0.101	-0.149
106U	0.183	0.054	-0.13
107U			
108U			
109U			
110U			
111U			
112U	0.25	0.087	-0.163
113Ui	0.2	0.184	-0.016
113Uii	0.1	0.061	-0.04
114U	0.175	0.018	-0.157
115U			
116U	0.225	0.076	-0.149
117U	0.225	0.009	-0.216
118U	0.229	0.039	-0.19
119U	0.2	0.093	-0.107

Figure 19: Data used to calculate accuracy per tooth surface in upper arch.

Lower Arch			
ID-Initial	Proposed IPR/S	Actual IPR/S	Difference/S
100L			
101L	0.1	0.105	0.005
102L	0.1	0.169	0.069
103L	0.233	0.101	-0.133
104Li	0.1	0.016	-0.085
104Lii	0.1	0.023	0.078
105L	0.25	0.035	-0.216
106L			
107L	0.15	0.109	-0.038
108L	0.15	0.168	0.018
109L	0.143	0.06	-0.083
110L	0.229	0.096	-0.132
111L	0.15	0.028	-0.122
112L			
113Li			
113Lii			
114L	0.2	0.129	-0.072
115L	0.214	0.012	-0.203
116L			
117L			
118L	0.213	0.075	-0.138
119L	0.15	0.126	-0.025

Figure 20: Data used to calculate accuracy per tooth surface in lower arch.

Appendix 7: Posterior/Anterior Segment Accuracy Divided by Number of Tooth Surfaces

Posterior Surfaces

ID-Initial	Proposed IPR/S	Actual IPR/S	Difference/S
100U	0.15	0.092	-0.058
101U	0.25	0.307	0.057
102U	0.175	0.42	0.245
103U	0.25	0.218	-0.032
104Ui	0.25	0.011	-0.239
104Uii			
105U	0	0	0
106U	0.25	0.103	-0.147
107U			
108U			
109U			
110U			
111U			
112U	0.25	0.181	-0.069
113Ui	0	0	0
113Uii	0	0	0
114U	0.1	0	-0.1
115U			
116U	0.25	0.08	-0.17
117U	0.25	0.001	-0.249
118U	0.2	0.022	-0.178
119U	0.25	0.023	-0.227
100L			
101L	0.1	0.105	0.005
102L	0.1	0.095	-0.005
103L	0.25	0.216	-0.034
104Li	0	0	0
104Lii	0	0	0
105L	0	0	0
106L			
107L	0.15	0.003	-0.147
108L	0.15	0.01	-0.14
109L	0.125	0.024	-0.101
110L	0.2	0.186	-0.014
111L	0	0	0
112L			
113Li			
113Lii			
114L	0	0	0
115L	0.2	0.007	-0.193
116L			
117L			
118L	0.25	0.185	-0.065
119L	0.15	0.177	0.027

Figure 21: Data used to calculate accuracy per tooth surface in the posterior segment.

Anterior Surfaces			
ID-Initial	Proposed IPR/S	Actual IPR/S	Difference/S
100U	0.15	0.063	-0.087
101U	0.25	0.126	-0.124
102U	0.221	0.125	-0.096
103U	0.25	0.094	-0.156
104Ui	0.25	0.018	-0.232
104Uii			
105U	0.25	0.101	-0.149
106U	0.177	0.049	-0.128
107U			
108U			
109U			
110U			
111U			
112U	0.25	0.072	-0.178
113Ui	0.2	0.184	-0.016
113Uii	0.1	0.061	-0.039
114U	0.186	0.02	-0.166
115U			
116U	0.221	0.075	-0.146
117U	0.223	0.01	-0.213
118U	0.233	0.042	-0.191
119U	0.195	0.099	-0.096
100L			
101L	0	0	0
102L	0.1	0.184	0.084
103L	0.23	0.077	-0.153
104Li	0.1	0.016	-0.084
104Lii	0.1	0.023	-0.077
105L	0.25	0.035	-0.215
106L			
107L	0.15	0.119	-0.031
108L	0.15	0.199	0.049
109L	0.146	0.066	-0.08
110L	0.233	0.082	-0.151
111L	0.15	0.028	-0.122
112L			
113Li			
113Lii			
114L	0.2	0.129	-0.071
115L	0.217	0.013	-0.204
116L			
117L			
118L	0.207	0.06	-0.147
119L	0.15	0.115	-0.035

Figure 22: Data used to calculate accuracy per tooth surface in the anterior segment.

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